Speaker building

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The aim of this project was it to built good stereo speakers for an acceptable amount of money. But what is “good”?
Good in our case means that the speakers have to be capable to reproduce various kinds of music faithfully, given all the other parameters like room acoustics are also capable of doing that. The range of music goes from Classic till Metal.
This is of course hardly possible as all the music in this rage asks for different requirements.
So our aim was it to built stereo speakers with a totally flat frequency response. Whereas the speaker itself should not sound flat but give the listener an experience of as much volume as possible in best case the speakers should be capable of reproducing concert hall experience – maybe at least like sitting directly in front of the musicians.
Therefore it is important that our speakers are free of distortion till the top end of a high dynamic range. And at the same time also the sound of silence should be clearly audible.
Of course those are not exactly very objective definitions of an aim, but as we built the speakers for ourselves we should be capable of deciding whether we did meet those goals or not. - We did! - But we can also for example measure the frequency response of the speakers to white noise and see whether it is really flat. Further we measured polar plots which show the mean radiated power in each direction per octave.

To summarize: We built two sets of stereo speakers and tested them.

Picking a design

As this was our first time to do such a project we decided to work on an already existing design. In this case the design of IAP Speaker Building at MIT with teachers Michael Price, Ken Stone and Hayami Arakawa (http://pricem.mit.edu/iap-speaker/).
We have chosen this design as one of us already listened to those speakers and judged their quality as: “amazing”.
Further from pure look the design seems to meet the general demands of a good speaker cabinet: Width, depth and hight are of different dimensions to prevent unnecessary strong resonances. Tweeter and woofer share the same vertical plane. The longest dimension has a baffle board what makes the design also more ridged. The box is vented to help with the lower frequencies. Simulations of the vented design were done, for results look in the part Analysis.
The crossover is also an already existing design from the same class and can be found on the same website. The measurement of the crossover output signal can be found under Analysis, too.

Building speakers

Took some time. But that is not the most important point here. Our very first step was to order a lot of parts from many different places (see list at the end of the report). Then we had to decide on a material for the enclosure or cavity. We picked Medium Density Fiber Board (MDF), which has two advantages: It is by far more homogeneous than normal wood, it is heavy, so it provides some inertia against the vibration of the sound field but it is also wood, at least in some sense, so it is easy to machine. And it is cheap. Easy to machine might be right, but it is a mess. Because of the fine dust it is best to wear a mask all the time. MDF does not like water. A damp rag can be used to wipe the dust of but not more. Otherwise it shows really ugly spots where it does not form a smooth surface anymore.
What to do with the MDF is straightforward and also bears some tricks, but we will make it short: We did cut the MDF it into pieces according to our construction plan. Hereby it is important to cut pieces of the same dimensions not that they are exactly the size the plan says. Then some holes must be drilled (in the right places – first and only mistake).
When the boards were cut and had holes for the tweeter, woofer, vent, speaker terminal and all the screws which should hold the tweeter, the woofer and the speaker terminal in place, we put T-nuts from the inside into the holes for the screws. Because MDF is not real wood – just glued compressed sawdust and hence not very capable of holding wood screws, especially when he are tightened too hard or the parts like woofer are taken out very often, then the wood screws would get very loose. At this place thanks to Alan for that hint.
Then we glued the enclosures together. We used a lot of glue and tried to clamp the boards together very tightly, always caring not to bend the boards while doing that. We did not glue all the enclosure at once but first the sides, the baffle board, top and bottom and in the next step front and back. Mounting front and back involved some fine tuning but everything fitted tightly together. It even cannot be seen that we patch worked one of the back boards (remember our first mistake) from two spare pieces.

In the next step we filled all little cracks and holes with wood filler (not those for the screws) and let it dry. Then we waited for a sunny day, which can be pretty difficult in Urbana's early spring. But with the first sun we went into the backyard and stared sanding for hours, went to lectures and sanded again. At this place thanks to Steve for helping us out with all the tools. After sanding we wiped the dust of the enclosures and painted them with several layers of latex based primer to give the MFD first protection. On the primer will later follow the real paint and our speakers will be unique.

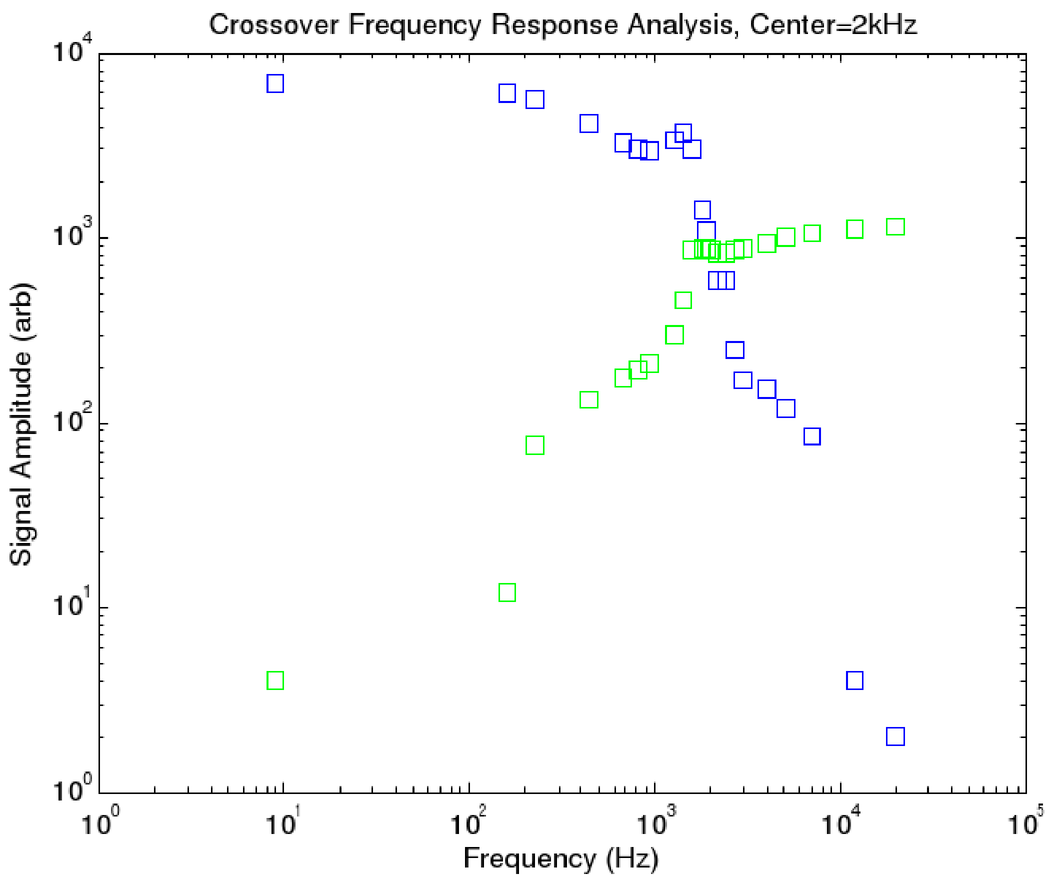
While waiting for the sun to come out we had enough time to solder the crossover components together and glue them to white board using Goop. (And we used a lot of it! Thank you Ben for this and all your other advises) Note that the inductors shall be mounted as far away from each other as possible and especially perpendicular to each other. After that we tested the crossovers (see Analysis).

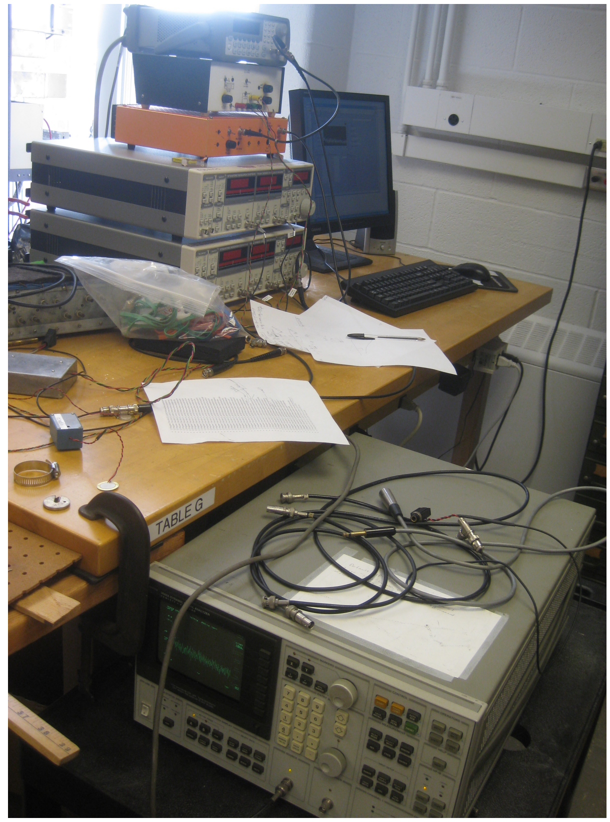
Before mounting all the parts into the enclosures we had to built holders for the PVC pipes forming our vent. This caused some trouble as we, at this point were not sure which length of pipe we were going to use (see Analysis). So we put those holders just loosely into place first and later glued them to the bottom of the enclosures. Then we mounted the pipes on the holders. Wired the speakers to the crossovers and those to the terminals. Note that the wires have to be twisted around each other in order to reduce fields created by the AC like sound signal. Also our cables are not attached to the enclosure but loosely wrapped in the damping material, see next paragraph.
This was the first time we could actually listen to our speakers then. And what we heard was great. Before that we had made the mistake to listen to one of the speakers with an open back and it sounded horribly flat. The tweeter was about okay but the woofer response was a failure.

As a last step we added damping fiber material in all the compartments of our enclosure to try to damp out the higher frequencies a little. Then we used Velcro to attach the crossovers to the inside of the sidewalls. (Thanks to Dave for this genius idea)

Analysis

The fist thing we analyzed was the frequency response of our 2nd order crossover. To be suitable the crossover frequency should be exactly somewhere around 2 kHz, as this is the frequency where on the one hand the woofer responses gets nasty just because frequencies become to high. But the tweeter on the other hand just starts working in that region. (See Dayton data sheets)
From the figure below, where we plotted the strength of the two channels of the crossover output (tweeter green, woofer blue) it can be seen that this aim was matched perfectly. The only noticeable thing about this plot is the difference in strength of the output signal, as both woofer and tweeter have nearly the same efficiency (88 and 89 dB at 1 W in 1 m distance). But this did not seem to be a real problem at this point as it can be expected, that the woofer radiates equally in all directions, whereas the tweeter is very directional. So the woofer will lose a lot of power in the forward direction to other spacial angles and like our polar plots (see below) show the intensity in the forward direction will be about the same for all frequencies.



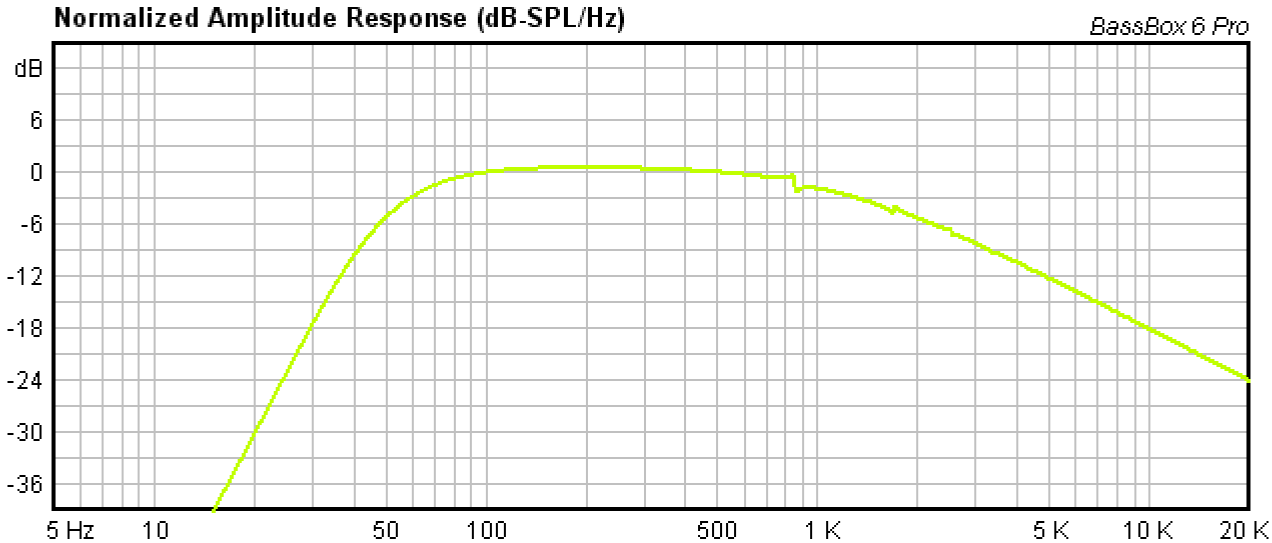


After building the cabinets our first questions was how long the pipe for the vent should be. And second we wanted to know whether damping would be necessary or not.

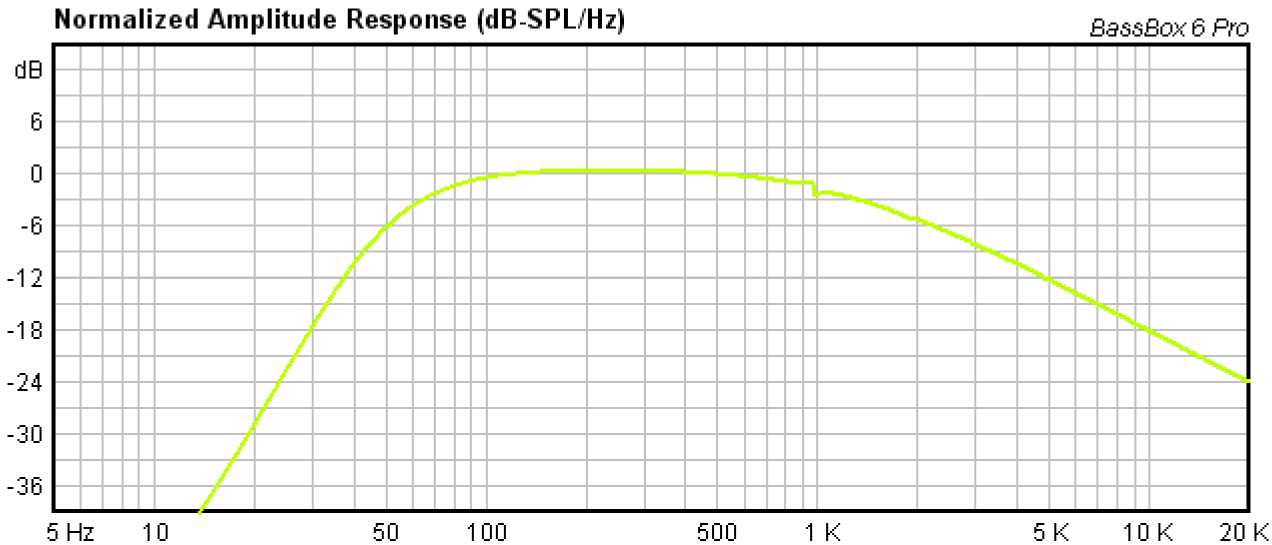
For solving those questions we first did a few simulations with the software BaseBox Pro 6. Those simulations were done to address the question of the pipe length. BaseBox Pro was a good option in this case as the vent is a part of the cabinet especially important for the lower frequencies not for the higher ones.
The simulation showed that larger pipe diameters are not favorable, as the dip around 1 kHz, which can also be seen for small diameters in the figures below, increases with the diameter of the pipe. So we decided to use a 2 inch PVC pipe like in the original design. The harder question was the length of the pipe, as simulations showed no significant variations with the simulated pipe length. This could have been expected, as the resonance frequency of a Helmholtz resonator obeys the formula:

$$\omega=\sqrt{\gamma\frac{P_0}{\rho}\frac{A}{V_0 L}}$$

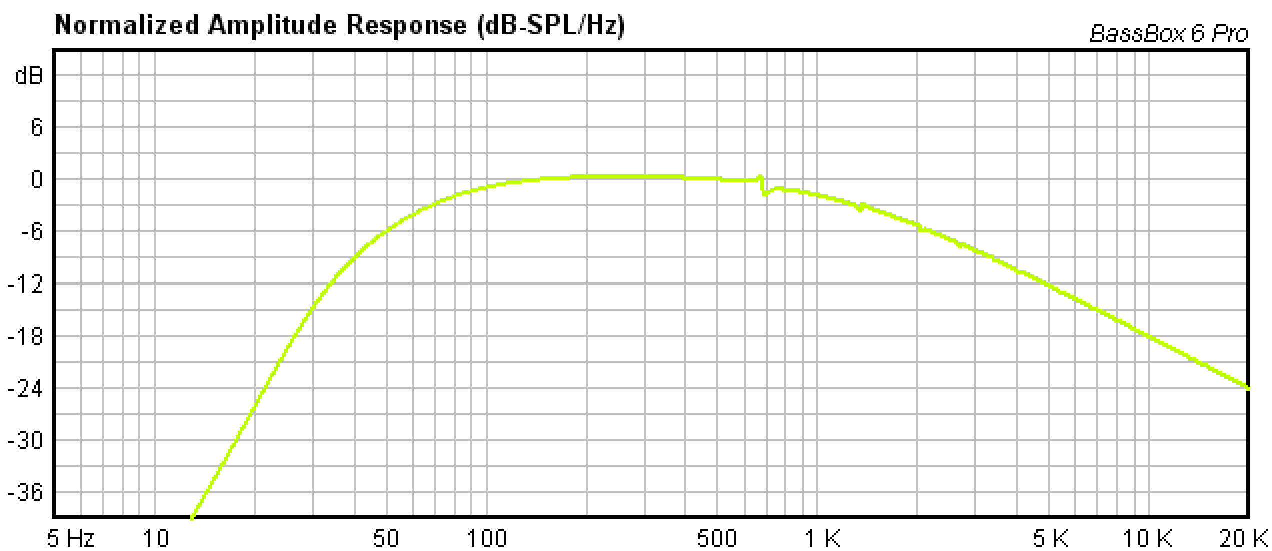
Hence the resonance frequency is proportional to the radius of the opening, but only proportional to the square root of the inverse of the pipes length.
The only conclusion we could draw was that it might be better to try smaller pipe length as those seem to shift the dip to higher frequencies and hence somewhere in the crossover region were the frequency response is either bad anyway or hopefully the tweeter has already taken over most of the power.
Also it can be seen that damping is expected to decrease the dip around 1 kHz a bit but does not do huge changes to the performance of the speakers.



5 inch pipe undamped



5 inch pipe heavily damped

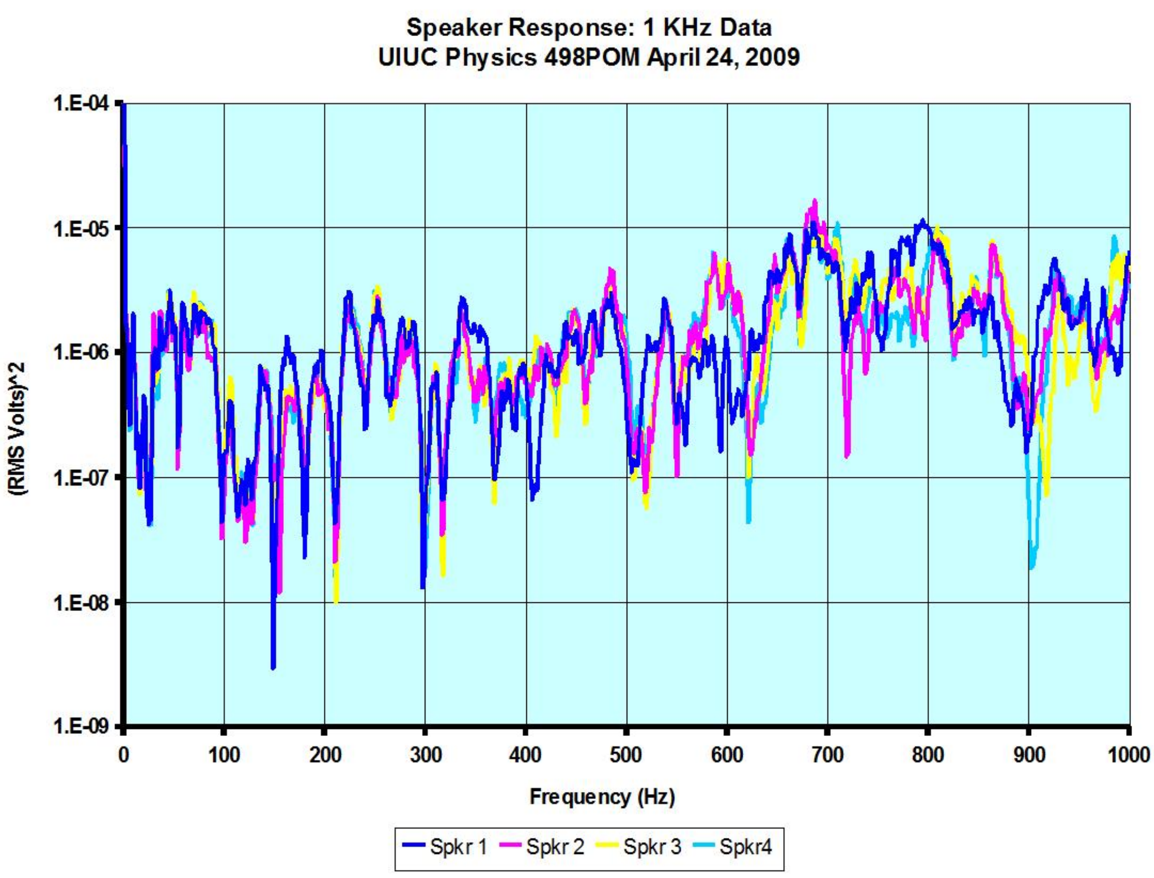


8 inch pipe heavily damped

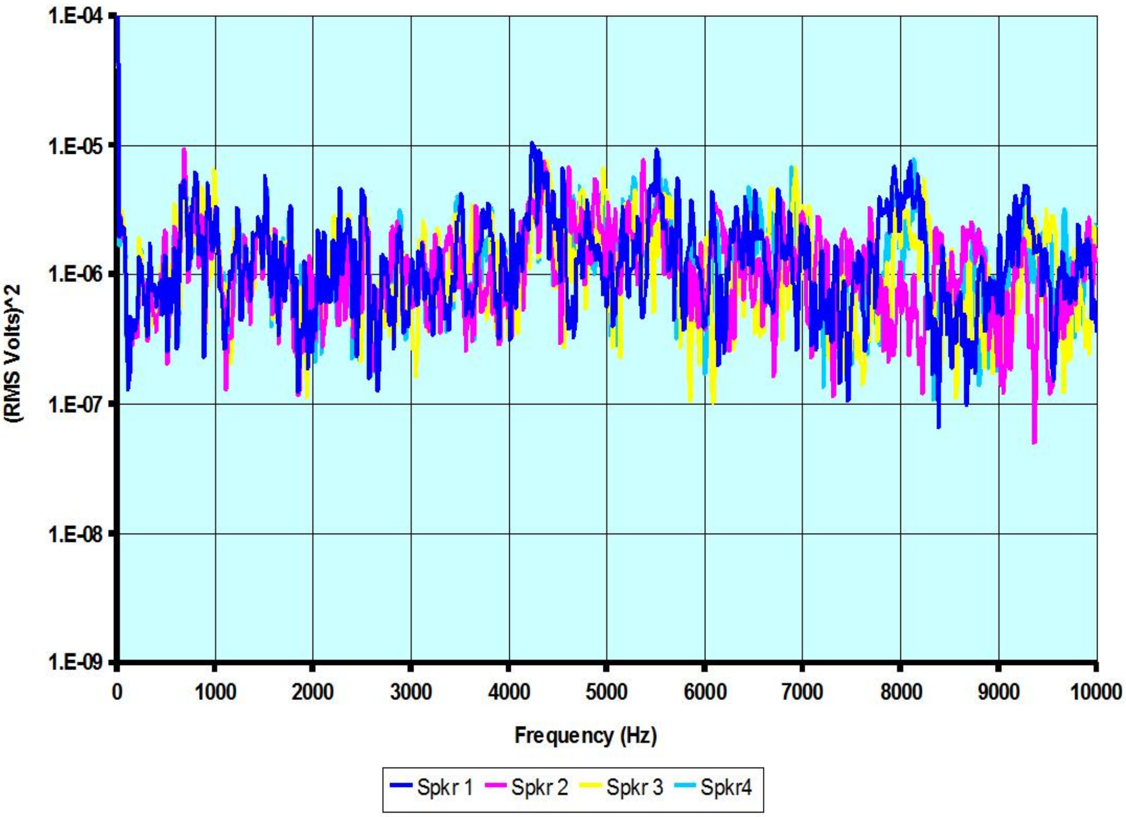
To get a definite answer we took our four speakers and equipped them all with different configurations regarding pipe lengths and damping:

Speaker 1:	6 inch pipe	(without damping material)
Speaker 2:	8 inch pipe	(heavy damping)
Speaker 3:	5 inch pipe	(heavy damping)
Speaker 4:	6 inch pipe	(heavy damping)

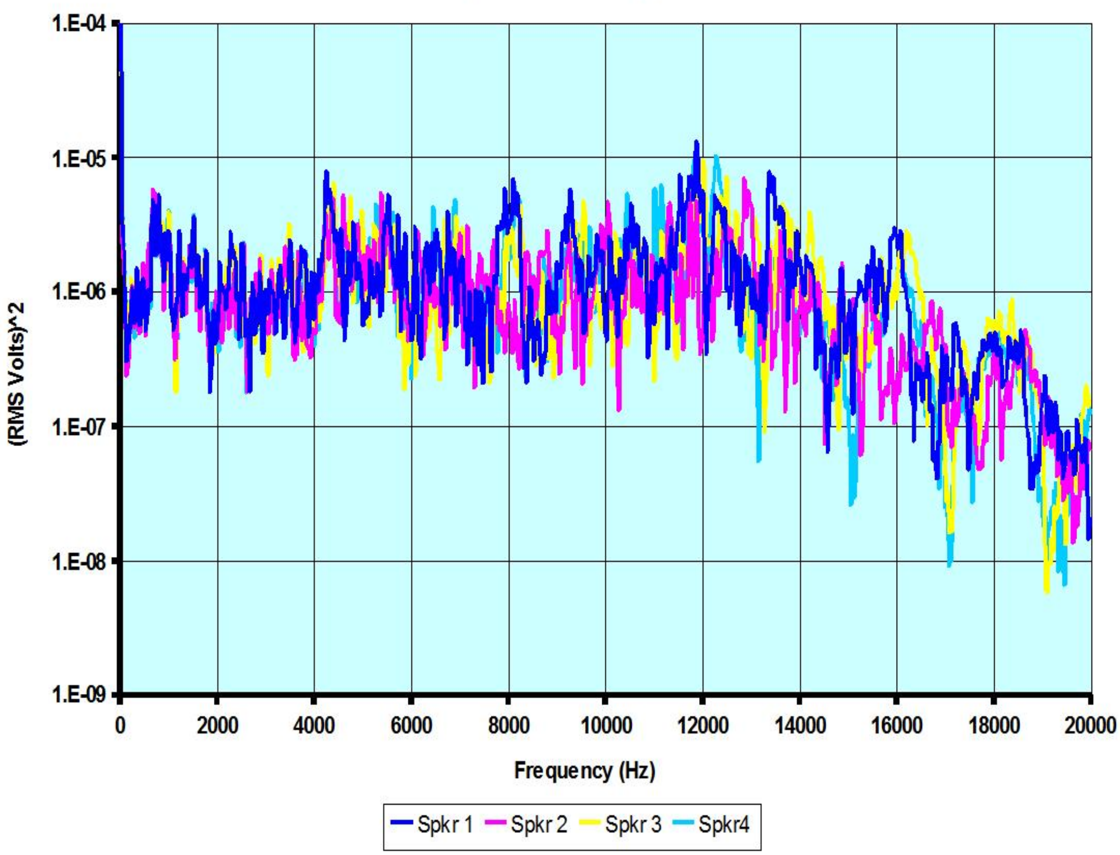
We took those speakers and measured their frequency response in the following way: We generated a white noise signal on a output of a spectrum analyzer and put this in an amplifier with known flat frequency response to drive our speakers. About 3 m away from the front baffle of the speaker the setup a reference microphone with an at least equally good frequency response the signal of this microphone was fed back to the spectrum analyzer which recorded the spectrum over 100 cycles. After the recording was finished the data was red out by a LabView interface and edited with Microsoft Excel.
For all measurements the speakers where driven at estimated 75% of full power. We obtained frequency spectra from 0 to 1 kHz, 2 kHz, 5 kHz, 10 kHz and 20 kHz. Those measurements were not free field but can contain room resonances, etc. Our only interest was to see differences between the different vented speakers, especially at low frequencies. A few of the spectra are shown in microphone output power over frequency in semilogarithmic scale.

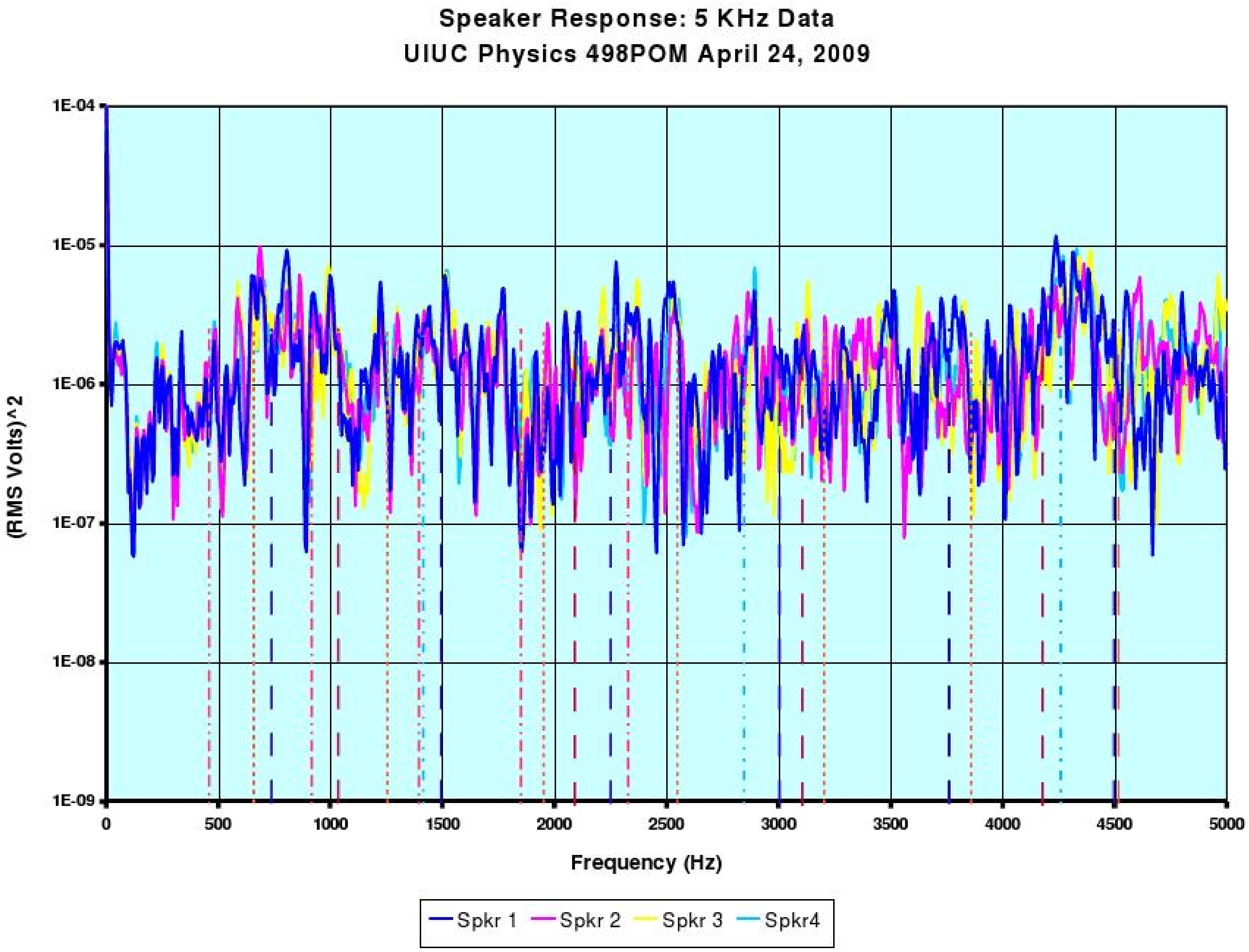


Speaker Response: 10 KHz Data
UIUC Physics 498POM April 24, 2009



Speaker Response: 20 KHz Data
UIUC Physics 498POM April 24, 2009



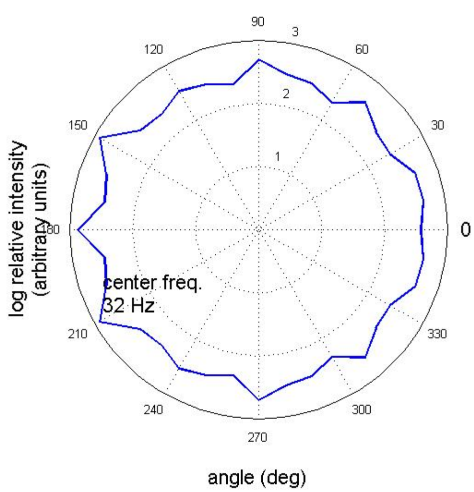


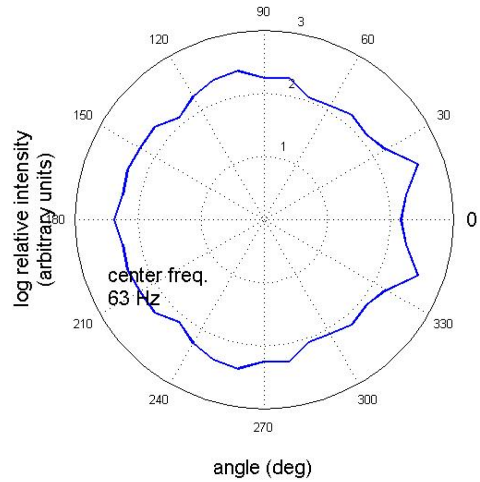
In general the response of the speakers is satisfyingly flat till about 14 kHz what should be enough for our purposes as first instruments are limited by their frequencies, e.g. violins can be played to bout 4 kHz what means that our speakers could reproduce till the second multiple of that tone very well. Second our own hearing range is limited to around 20 kHz so all we would miss is roughly one harmonic in a frequency range we are possibly not even very sensitive to. Even the damped and undamped 6 inch design show now significant differences in performance. Maybe the undamped design peaks higher at high frequency resonances but otherwise all designs seem to be pretty even. To relatively help the lower frequencies a little more we decided to choose the heavy damped design.
It should be noted here, that the crossover which is at 2 kHz cannot, or barely be made out in the spectrum.
The last plot showing the 0 to 5 kHz region compares the measured spectra with locations at which resonances could be due to spacial dimensions of the enclosure. Whereas the red lines stand for the following dimensions of the enclosure: Dash dotted: Height; Dotted: Depth; Dashed: Width. The blue lines stand for possible resonances due to the baffle board. Here we only looked at resonances between two opposite walls. Not at resonances involving more walls. There is no real pattern visible. The only thing that can be said is that the lines are often near peaks in the spectrum but they are very often at significant dips, too.

To give the analysis a nice finish we decided to try the measurements of polar plots, even though we were not able to measure in free field, but, as it can be seen in the pictures, we tried the best to damp from walls reflected sound.
For the measurements we took the same setup as before, we only changed the distance of the reference microphone to exactly 1m from the central vertical axis of the speaker around which we rotated the later in the following by steps of 10 degrees. The output of the reference microphone was again fed to the spectrum analyzer and red out by the LabView interface. We then calculated the average intensity over octaves with center frequencies of from 32 Hz, 63 Hz to 8000 Hz for each angle and plotted those intensities relatively to the lowest measured logarithmically with MatLab. The units of the results seen below are hence Bell.
It should be noted that only the angles from 0 to 180 degrees were measured and the response then assumed to be symmetric.
We want to note again that those were not free field measurements so the results are only to be taken qualitatively. Nevertheless one can clearly see how the directivity increases with frequency. For low frequencies the speaker radiates nearly radially symmetric but for frequencies above 250 Hz the radiation becomes more and more directional till for 8000 Hz the speaker almost only radiates in a cone with 120 degree opening angle.
Those polar plots also confirm our measurements above as they show that for the forward direction the output of the speaker just slightly varies with frequency.

As a very last test we had several physics students listening to our speakers and the result seems to be pretty okay.

Polar plots for Speaker 4:

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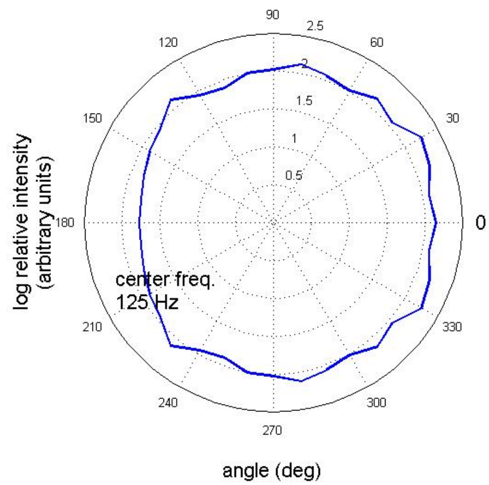
angle (deg)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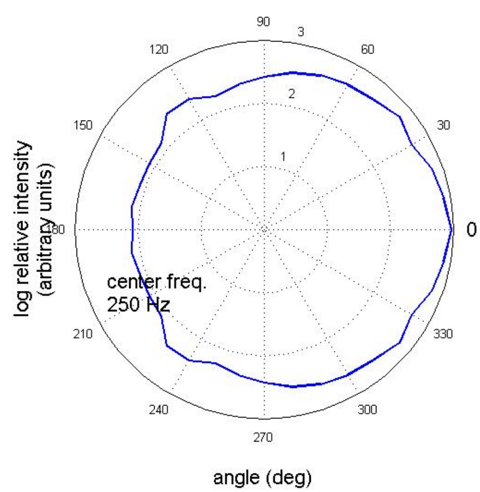
angle (deg)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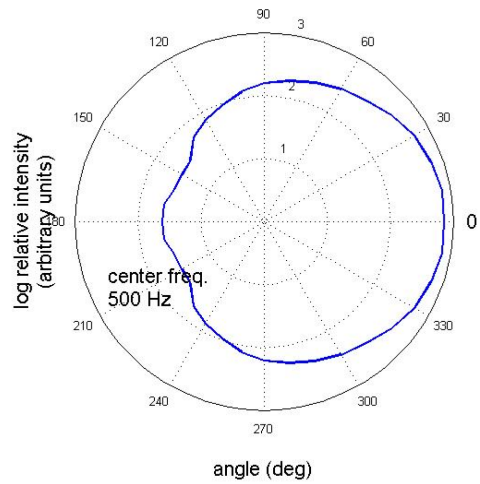
angle (deg)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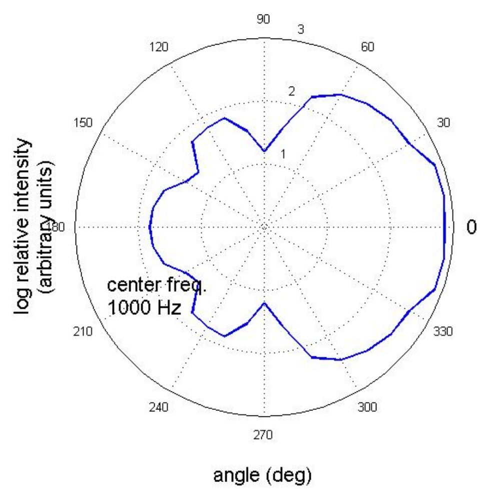
angle (deg)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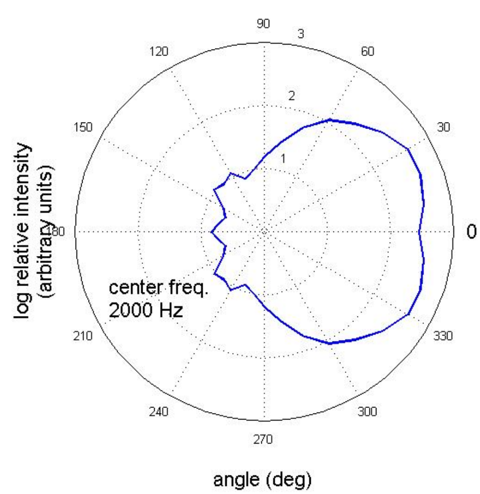
angle (deg)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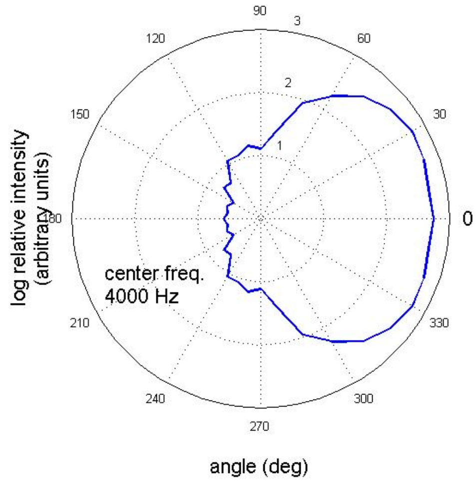
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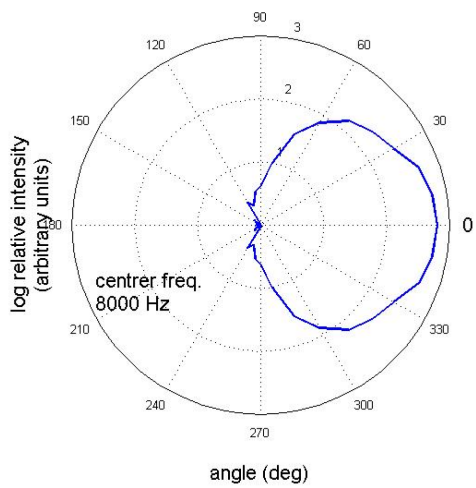
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angle (deg)

Parts for 4 Speakers:

PartsExpress:

No. of Parts	**Part No.**	**Part**	**Price per piece**
4	275-070	Dayton DC28F-8 1-1/8" Silk Dome Tweeter	
4	295-362	Dayton RS150S-8 6" Reference Shielded Woofer 8 Ohm	
8	027-428	Dayton DMPC-10 10uF 250V Polypropylene Capacitor	
4	255-032	Jantzen 0.40mH 20 AWG Air Core Inductor	
4	255-264	Jantzen 1.8mH 18 AWG Air Core Inductor	
1		Shipping	

Antique Electronics:

No. of Parts	**Part No.**	**Part**	**Price per piece**
4		Resistor 3,3 ohm	
4		Resistor 5,0 ohm	
1		Shipping	

LOWE'S:

No. of Parts	**Part No.**	**Part**	**Price per piece**
1		Medium Density Fiber Board	$25.00
1		Wood Glue	
1		Sanding Paper 100	
1		Sanding Paper 150	
1		Primer Latex based	
1		Epoxy	
2		Goop	
1		Wood filler	
2		Masks	

McMaster

No. of Parts	**Part No.**	**Part**	**Price per piece**
1		T-Nuts	
1		Shipping	

JoeAnn's Fabrics

No. of Parts	Part No.	Part	Price per piece
1		Polyfill	

And

No. of Parts	Part No.	Part	Price per piece
		Velcro	
		Wire	
		Screws	