Loudspeaker Research & Design – HSD5

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FA4740: Transducer Theory

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Functional Description

Requirements & Goals

The following paper outlines the designs, processes, and explanation behind the loudspeakers that I will be designing & building during my last semester at Michigan Technological University.

The loudspeakers will be used for relaxation, chilling, pleasure, and enjoyment. Their uses will include listening to background music, watching TV shows, watching the occasional movie, listening to a new CD, playing video games, and other "daily use" purposes. The loudspeakers will have to work in specific environments: a living room and an office/bedroom. The first is an absolute must – the loudspeakers must be able to fill a typical living room with sound whether one or ten listeners are present (they should have a wide range for the "sweet spot"). The second location is a secondary environment that would possibly be implemented, depending on the arrangement of the house. The loudspeakers should be able to function quite similarly in a close listening position as they would in a distant listening position. The loudspeakers should be able to overpower any room noise from heating vents, AC units, fans, etc. As well, they must be able to overcome any external noise coming from other rooms of the house, other inhabitants, or noises coming from outside the house. The loudspeaker should be able to be placed on pedestals or a TV while operating in the living room and would be placed on pedestals if used in an office/bedroom. The loudspeakers will need to operate as a stereo pair with the option & ability to add an external subwoofer when extremely low frequencies are desired in music or movies.

The loudspeakers should remain relatively portable as they will need to be moved throughout various houses (over the long-term) and should be able to be listened to in multiple rooms that may be separated by stairs or narrow hallways. One loudspeaker should take no more than one person to carry and should be able to be carried with one arm. The loudspeakers should be able to maintain an effective sound across an array of treated and non-treated rooms. Special care will be taken when placing the loudspeakers in rooms, even though little to nothing is known about any of the conditions of possible rooms that they may be placed in. However, a wide "sweet spot" is specifically desired. The loudspeakers will be used for extended periods of listening over multiple hours. The loudspeakers need to function for long periods of binge-watching NETFLIX™ or lazy Sundays filled with video games and football games. Although the loudspeakers will be used purely for enjoyment, they should still be able to accurately recreate any content that they reproduce with little to no coloration. Thus, if the loudspeakers were to be used in a mixing environment, their intended use would be for listening back to the original sound sources[1]. The final product should be a set of relatively Hi-Fidelity loudspeakers that are specifically used for enjoyment.

Similar to Moulton's idea of listening back or listening forward is Moulton's idea of the range rule[2]. This theory is based on the idea of considering all of the possible loudspeaker systems that the end-user may be utilizing to listen to a product. However, since my loudspeakers focus on an accurate translation of the listening content, this is not something being taken into consideration during the design process.

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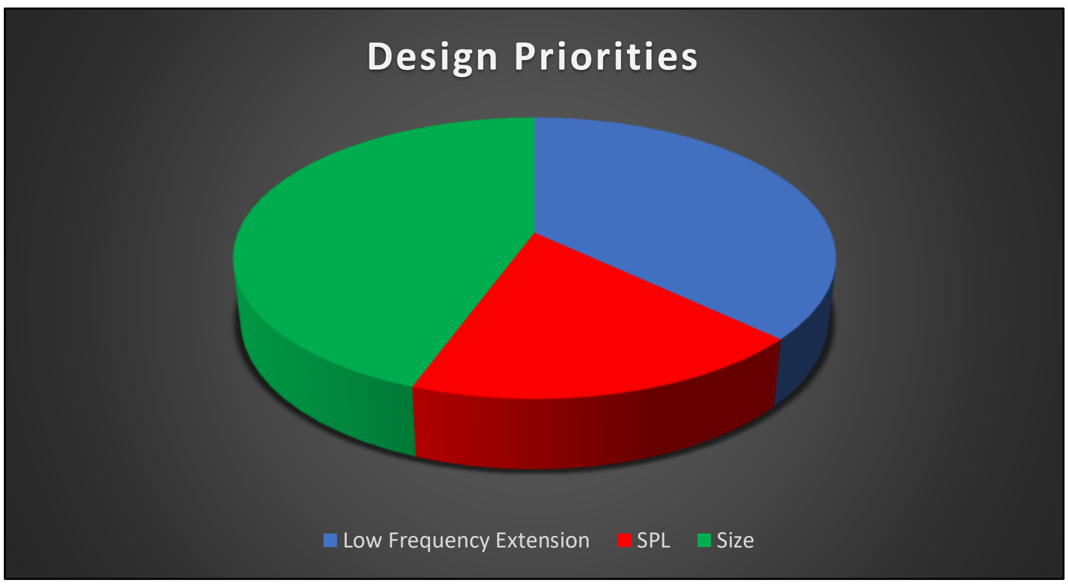
[1] Moulton, David. *Total Recording: The Complete Guide to Audio Production and Engineering.* KIQ Productions, Inc. 2000. 313-314.

[2] Ibid, 315-316.

The loudspeakers need to be constructed out of a material - preferably wood - that is easily painted with a small number of coats for complete coverage. The loudspeakers will be rectangular boxes that are taller than they are wide and with a depth that is less than the height. This design is to allow placement on both pedestals and TV stands and to accommodate a range of listening positions, whether the listener is standing or sitting. As previously stated, the loudspeakers should remain portable: a single speaker is required to be able to be carried by one person at a time. However, the design should still remain compact enough to allow placement in a wide range of locations. The loudspeakers are designed to be used mainly in frequently occupied locations in the house and should offer some form of protection from pets, children, party-goers, liquids, etc. through the use of speaker grills and a semi-waterproof coating on the top of the speakers.

Design Tradeoffs

The following diagram is a pie-chart of my prioritization of the loudspeakers, based on John Murphy's ideas of Loudspeaker Design Tradeoffs[3]:



As can be seen in the above diagram (on the previous page), the main priorities for loudspeakers are Low Frequency Extension & Size (with Size taking a slightly larger slice of the pie than Low Frequency Extension). These priorities have been determined based on my need for full-range, accurate loudspeakers that are still portable and easily moved between houses and multiple rooms.

[3] Murphy, John L. *Introduction to Loudspeaker Design*. II. Andersonville, TN: True Audio. 2014. 61-63.

Technical Specifications

Size

Dimensions

Television placement varies in just about every house you visit (almost as much as the size of the television varies). For the purposes of this paper, I will be basing a majority of my measurements around a 48" display with relatively small bezels (as this is the TV that I currently own). I typically keep the TV anywhere from 2' to 4' above the ground (always placed on an "entertainment cabinet" or similar piece of furniture) and the seated head-height will typically align with the center of the TV or slightly lower (but with the seating as wide as 180^0 in front of the TV).

The typical height for a TV with a 48" display is 2' (from the bottom bezel to the top bezel)[4]. I usually keep my TV on the factory stand which adds 2" to the overall height resulting in a total TV height of 26". I want my loudspeakers to retain a similar height to the television (although I will most likely not have a 48" TV for the rest of my life) and therefore my ideal speaker height would be 28" tall (2 inches below and above the bezels of the TV). However, a 32" TV will be about 16" tall and a 60" TV will be 30" tall. Therefore, I wouldn't want my loudspeakers to be any shorter than 16" and no taller than 30".

The typical width for a 32" TV is 28" and 52" for a 60" TV[5]. Due to the unpredictable nature of future living room setups, I want to save space on the sides of my television. Therefore, the maximum width I would want to build is 10" (10" + 10" + 52" = 6' wide) and a minimum width of about 6" (as I don't want the loudspeakers to appear awkwardly tall).

I do not have a specific depth in mind for the cabinets of my loudspeakers, however, I don't want them to be excessively long (as they still need to be able to be carried by a single person). A majority of the stereo receivers, CD players, radio tuners, DVD players, and game consoles I own are all 18" or less in depth. Therefore, I want my loudspeakers to be 18" or less deep – with the depth no less than the width.

Maximum Size (HxWxD): 30" x 10" x 18"

Minimum Size (HxWxD): 16" x 6" x 6"

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[4] Demers, Cedric, and Mehdi Azzabi. 2017. *TV Size to Distance Calculator and Science.* May 26. Accessed February 5,
2019. https://www.rtings.com/tv/reviews/by-size/size-to-distance-relationship.
[5] Ibid.

Volume

My ideal construction will consist of ½" MDF & ½" Plywood to maximize my internal volume. Unfortunately, I plan to utilize Mini DSP ICE plate amplifiers in my design which would take up a significant amount of volume inside the cabinets. Therefore, I will be mounting them in separate enclosures and only subtracting 1" from all of my sides to determine my internal volume. Therefore:

Maximum Volume: 2.074 ft^3

Minimum Volume: .1296 ft^3

Weight

I tested the weight of three "studio monitor" loudspeakers to determine a range of acceptable weights that I will aim for when designing my loudspeakers. All of the speakers that I chose are small, desktop loudspeakers that could be carried with only one arm. The first loudspeaker was a *Yamaha HS8*, weighing approximately 28lbs. I thought the loudspeaker was very easy to move and I could easily lift it over my head. The second loudspeaker was a *Behringer Truth B2301a*, weighing approximately 35lbs. This loudspeaker felt significantly heavier than the HS8's due to its smaller size and concentrated plate amplifier. Finally, I picked up my roommate's (Michael Chopp) custom built speakers that weigh just under 50lbs.

After carrying all three loudspeakers around for a short while I determined that 50lbs was going to be the maximum weight I will be able to accept (especially knowing that my loudspeakers are going to take on an oblong shape). If the loudspeakers weigh any more than 50lbs they will most likely be too difficult to carry with one arm and make it up & down staircases. However, I have no minimum weight requirements, so I'll be aiming to make them as light as possible (which will be helped by mounting the DSP/plate amplifiers outside of the enclosure).

Maximum Weight: 50lbs

Minimum Weight: None

SPL

The following information was tabulated during a weeklong listening experiment in which I explored my preferred listening levels. I conducted a majority of my SPL Listening while in my bedroom – this is where I found myself listening to most of my music during the test period. I managed to perform a few listening experiments in my living room, but I discovered that my preference was relatively similar in both spaces. My test content ranged from Death Metal to Folk Rock (as I shuffled through my iTunes Library) and I monitored a few YouTube Videos & TV Shows.

The table below displays the averaged data based on certain times throughout the day:

Time:	SPL Preference (dB):
10:00am	67
11:00am	74
8:00pm	69
9:30pm	80
10:30pm	62.5
11:30pm	70
1:00am	67

The table below displays the averaged data based on mood:

Mood:	SPL Preference (dB):
Happy/Good	75
Chill	70
Poor/Bad	80

I calculated my typical listening SPL to be around 75dB at 1 meter from the loudspeakers. However, I plan to install my loudspeakers in living rooms of various sizes and I want to plan for the worst-case scenario. Therefore, I would most likely want my loudspeakers to constantly produce an output level of 75dB SPL at the listening position, 4 meters away from the loudspeakers (my current living room setup placing the listener approximately 8ft, 2.4m, from the loudspeakers). I will then again assume the worst-case scenario wherein I will be losing 6dB for every doubling of distance past 1 meter from the speaker and calculate my required average output to be 87dB SPL (at 1 Watt at 1 Meter). However, an average output of 87dB SPL does not take into consideration any amount of available headroom. Typical "pop" music listening environments require at least 12dB SPL of headroom (for peak amplitudes of 99dB SPL based off my calculation of 87dB SPL average output)[6].

[6] Katz, Bob. 2000. "Level Practices." *Digital Domain.* Accessed 2, 6, 2019. www.digido.com. 6-7.

Based on research performed by Bob Katz, it has been shown that a level of 83dB SPL at the mix position, with an additional 20dB of headroom, can result in extremely desirable mixing conditions[7]. Although I will not be using my loudspeakers for recording, mixing, or mastering, I would like them to be capable of matching the K20 scale that is extremely similar to THX standard for loudness reproduction[8]. Therefore, my new driver average output requirement is (once again assuming a 6dB loss for every doubling of distance) 95dB SPL. My amplifier choice will then need to supply at least 20dBw to allow my drivers to perform with a peak SPL output of 115dB.

Minimum Driver Sensitivity at 1 Watt at 1 Meter: 87dB SPL

Maximum Driver Sensitivity at 1 Watt at 1 Meter: 95dB SPL

Minimum Amplifier Output: 20dBw (100W)

Maximum Amplifier Output: None

[7] Ibid. 6-7.

[8] Ibid. 4-5.

Frequency Response

High Frequency Extension

I have no hard-set requirements for the high frequency extension of my loudspeakers. The most important requirement for my tweeters is to have a consistently flat off-axis response up to, at least, 16kHz. This will allow better off-axis listening (as a majority of listeners will be significantly off-axis) with more than enough frequency range (as critical listening will still take place directly on-axis).

Minimum Tweeter High Frequency Extension: 16kHz

Maximum Tweeter High Frequency Extension: No Limit

Low Frequency Extension

The following information was collected during a listening experiment performed in Walker 210 on Michigan Tech's campus. The following songs were used during the testing period:

1. I Found, *Amber Run*
2. Pilgrim, *Good Harvest*
3. Woodstock, *Good Harvest*
4. Fast Company, *Eagles*
5. O.D., *Polyphia*
6. Seeya, *Deadmau5*
7. Red Cold River, *Breaking Benjamin*
8. She's American, *The 1975*
9. The Pot, *Tool*
10. Periscope, *Papa Roach*
11. Till It's Gone, *Yelawolf*
12. Emotional Drought, *Chevelle*
13. A Lack of Color, *Death Cab for Cutie*

I included songs like *Seeya, O.D., The Pot,* and *I Found*, because of their extended frequency ranges that are a must if listening. Songs such as *Woodstock* and *A Lack of Color*, have very little taking place below 60Hz or 70Hz and were used to balance out my listening spectrum. All songs were listened to with both a 6dB/Octave and an 18dB/Octave low cut filter at different frequencies to determine a "Noticeable" frequency, an "Acceptable Range" of frequencies, and an "Unacceptable" frequency. All of the tracks were listened to approximately 10ft from the speakers with peak levels kept between 76dB & 80dB (based off of my SPL Listening Preferences).

The following table contains all of the quantitative data (measured in Hz) from my listening experiment:

		6dB/Octave Low Cut				**18dB/Octave Low Cut**	
	Noticeable:	Acceptable Range:	Unacceptable:		Noticeable:	Acceptable Range:	Unacceptable:
I Found	35	35 - 60	80		30	30 – 50	60
Pilgrim	50	50 – 100	120		54	54 – 80	85
Woodstock	60	60 – 100	120		80	80 – 110	120
Fast Company	36	35 – 60	90		37	37 – 65	75
O.D.	30	30 – 60	75		33	33 – 65	75
Seeya	26	26 – 50	50		28	28 – 65	65
Red Cold River	34	34 – 65	75		34	34 – 50	50
She's American	39	39 – 80	90		45	45 – 75	75
The Pot	30	30 – 85	95		40	40 – 80	80
Periscope	30	30 – 85	90		40	40 – 60	60
Till It's Gone	34	34 – 70	70		40	40 – 65	65
Emotional Drought	40	40 – 85	90		42	42 – 72	70
A Lack of Color	90	90 – 120	120		80	80 – 120	130

Based on of this data, the maximum F_3 in a vented box that I "live with" to build would be approximately 65Hz. The data would then suggest a minimum F_3 of around 35Hz; however, I do not have a minimum F_3 requirement that can be based on my personal preferences (that value will be based off my size constraints).

Maximum F_3: 65Hz

Minimum F_3: None

Time Response

I did not bother to address my listening preferences for a 6dB/Octave Low Cut filter (simulating a sealed box) because I have decided that I will be building a ported/vented loudspeaker to fulfill by SPL & Low Frequency Extension requirements while remaining within my size limitations. Therefore, I am willing to accept the loss in low frequency accuracy to achieve this goal (even though this goes against the idea of "listening backwards" with my loudspeakers, I will still not be using them for recording, mixing, or mastering)[9].

I will be building my loudspeakers to have an extended shelf response, via the final port tuning (which will be complimented with a 2.5-way design to maximize low frequency response). Due to the port length that will most likely be required, I will be mounting the port on the back of the loudspeakers to prevent any unwanted reflections from coloring the sound. As well, since the loudspeakers will be placed next to a TV on a TV stand, I will not have to worry about placing them too close to a rear boundary (some foam will most likely be added behind the loudspeakers to help cut down on any reflections that may escape). As a further precaution, I will be filling the enclosure with fiberglass insulation to cut down on even more internal reflections.

Driver Mounting

The ideal driver mounting positions consist of placing the tweeter at least halfway up the enclosure, thus allowing the listening access to remain around the center of the loudspeakers. A dual woofer loudspeaker is desired; therefore, the tweeter will be placed in between the two woofers (in the exact center of the enclosure). All drivers will be mounted inset within the front baffle, allowing the baffles/casings of the drivers to be flush with the loudspeaker's baffle (thus eliminating any undesired diffraction caused by an alignment-mismatch). In addition, all drivers will be kept within a half-wavelength of the final crossover frequency to avoid any unwanted coloration (due to unwanted comb-filtering).

The sides of the front baffle will, ideally, have their edges rounded over to smooth out the transition as sound waves interact with the edge of the baffle (hopefully preventing some amount of unwanted diffraction). However, my current plan consists of utilizing plywood as the front baffle which may render this plan impossible/extremely difficult.

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[9] Moulton, David. *Total Recording: The Complete Guide to Audio Production and Engineering.* KIQ Productions, Inc. 2000. 313-314.

Design

Drivers

Woofers

Never before has a decision weighed so heavily on my mind. It took me an astronomical amount of time to compare drivers as I argued back and forth with myself over Size vs. Low Frequency Extension. I spent time looking at 6”, 6.5”, 7”, and 8” drivers before realizing that my initial design and hard-restrictions would not allow me to use these drivers (although multiple instances saw my drivers producing an F_3 of below 20Hz while I explored the 8” drivers). I eventually returned to some of the hard and fast truths of my initial loudspeaker design: nearly 8” wide, dual-woofers, and lightweight. Upon reflection, I was able to discover the four drivers that I have narrowed my search to; three drivers that fit within my size constraints and one driver that was able to stand out against the rest.

The following table displays all of the woofers that I had modeled in *Winspeakerz* while searching for the ideal driver. However, I left out information for a majority of the 6” woofers after I realized that the 1.875ft^3 enclosure that I had modeled them in was too big to fit within my re-defined size constraints. The bottom driver, high-lighted in gray, is the SB Acoustics SB15CAC30-4 that will become the driver in my realized loudspeaker design (as explained in the rest of this section).

Woofer Price:	Woofer Manufacturer:	Woofer Model:	Woofer Size:	Woofer Impedance:	Cabinet Size:	F3 (Hz):	Type of Bass:	Unusable Frequency:	Thermal SPL Limit:	Mechanical SPL Limit:	Highest Crossover Frequency:
$ 86.50	SB Acoustics	SB17CAC35-4	6"	4	1.875 ft^3	35	Extended Shelf	29	107.8	111	2.5k
$ 86.50	SB Acoustics	SB17CAC35-8	6"	8	1.875 ft^3	34	Critically Damped	28	104.3	106.5	2.5k
$ 93.95	SB Acoustics	SB17CRC35-4	6"	4	1.875 ft^3				107.8		2k
$ 93.95	SB Acoustics	SB17CRC35-8	6"	8	1.875 ft^3				104.8		2k
$ 27.80	SB Acoustics	SB16PFC25-8	6"	8	1.875 ft^3				103		2k
$ 60.30	SB Acoustics	SB17MFC35-8	6"	8	1.875 ft^3				105.8		1.5k
$ 70.45	SB Acoustics	SB17NBAC35-4	6"	4	1.875 ft^3				107.8		2k
$ 64.80	SB Acoustics	SB17NRX2C35-4	6"	4	1.875 ft^3				107.8		1.7k
$ 88.50	SEAS Prestige	CA18RNX H1215	6.5"	8	1.875 ft^3				107.5		4.5k
$ 100.50	SEAS Prestige	L16RN-SL H1480	5"	8	1.875 ft^3				103		2k
$ 93.60	SEAS Prestige	L18RNX/P H1224	6.5"	8	1.875 ft^3				108		2k
$ 95.60	SEAS Prestige	U16RCY/P H1520-08	5"	8	1.875 ft^3				104.8		2.5k
$ 66.85	SB Acoustics	SB15NBAC30-8	5"	8	1.13 ft^3	37	Extended Shelf	33	102.5	105.5 (105 @ rolloff)	3k
$ 80.70	SB Acoustics	SB15CAC30-8	5"	8	1.13 ft^3	37	Critically Damped	33	103	106	3k
$ 66.85	SB Acoustics	SB15NBAC30-4	5"	4	1.13 ft^3	37	Extended Shelf	32	105	108 (106 @ rolloff)	3k
$ 80.70	SB Acoustics	SB15CAC30-4	5"	4	1.13 ft^3	36	Extended Shelf	30.5	105	108 (106 @ rolloff)	3k

Values generated in Winspeakerz[10]

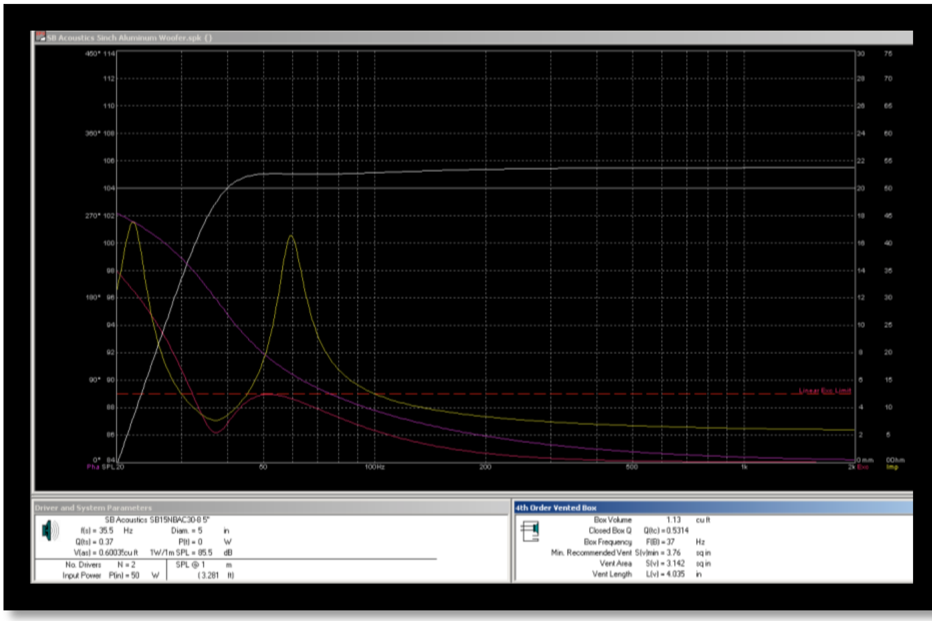
All four of my finalist drivers are manufactured by SB Acoustics. After hearing a few of their different drivers I felt confident enough to put my trust in the company and I was not disappointed. SB Acoustics makes a wide range of small drivers with high sensitivities, low Fs numbers, and comparably large Vas values. I wanted to maximize as much low frequency extension out of as small a driver as possible without experiencing high amounts of distortion (everyone’s dream). Luckily, I don’t require an extremely low F_3 value, and all four drivers put me a few hertz below 40Hz in my desired cabinet size.

[10] TrueAudio. 2008. *Winspeakerz.* Andersonville.

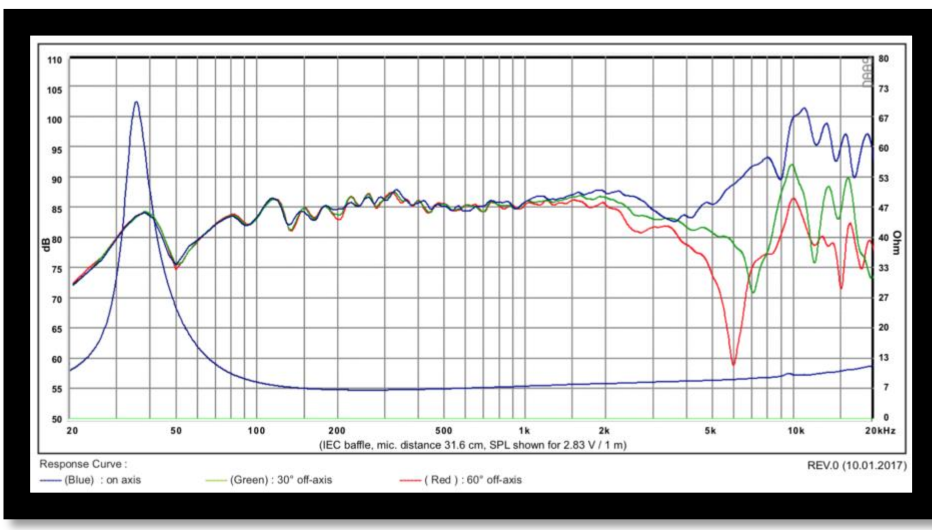
SB Acoustics SB15NBAC30-8

5" Aluminum Cone Mid-Bass Woofer

SB Acoustic's 5" aluminum cone woofer had almost everything I desired. It was black, had an Fs below 40Hz, had a 5mm excursion (I had discovered that 5mm to 6mm excursion on a 5" or 6" driver was the "sweet-spot"), and had relatively low Qts & Qes factors. However, it only has a sensitivity of 85.5dB at 1 meter with 1 watt of power. Even though my dual woofer design could get me an output close to 105dB (at 1 meter with 50W of power), an F_3 of 37Hz had me wanting more. [11]



Simulation performed by Henry Sendek in Winspeakerz by TrueAudio[12]



Frequency Response Plot taken from SB Acoustics 5" SB15NBAC30-8 Spec Sheet[13]

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[11] SB Acoustics. 2010. Accessed February 20th, 2019. *SB Acoustics: 5" SB15NBAC30-8.* http://www.sbacoustics.com/index.php?cID=233

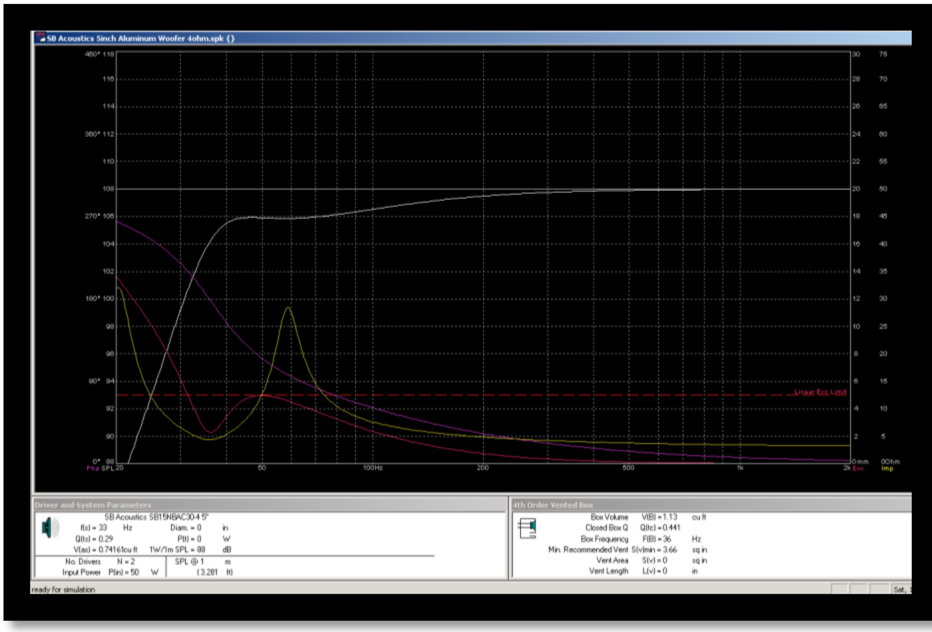
[12] TrueAudio. 2008. *Winspeakerz.* Andersonville.

[13] SB Acoustics. 2010. Accessed February 20th, 2019. *SB Acoustics: 5" SB15NBAC30-8.* http://www.sbacoustics.com/index.php?cID=233

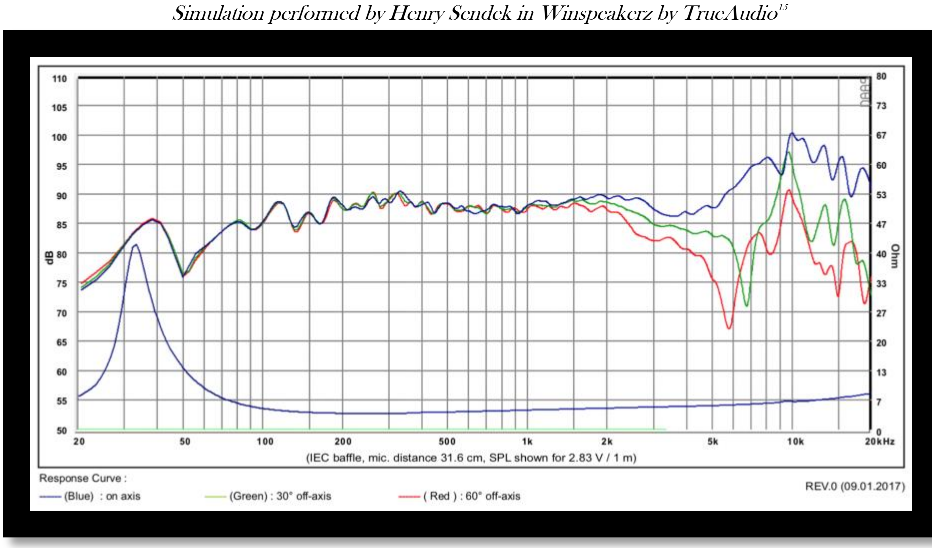
SB Acoustics SB15NBAC30-4

5" Aluminum Cone Mid-Bass Woofer

The four-ohm version of the SB Acoustics 5" aluminum cone woofer had more of what I wanted (but by a small margin). The dual-woofer scenario produced another F_3 of 37Hz with a maximum output of 106dB. Unfortunately, this 106dB was actually thermally limited to 103dB as the enclosure I was modelling would be able to push the driver harder than its thermal limiting would allow (of course these are still long-term values, but it helps to paint a better picture).[14]



Simulation performed by Henry Sendek in Winspeakerz by TrueAudio[15]



Frequency Response Plot taken from SB Acoustics 5" SB15NBAC30-4 Spec Sheet[16]

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[14] SB Acoustics. 2010. Accessed February 20th, 2019. *SB Acoustics: 5" SB15NBAC30-4.* http://www.sbacoustics.com/index.php?cID=232

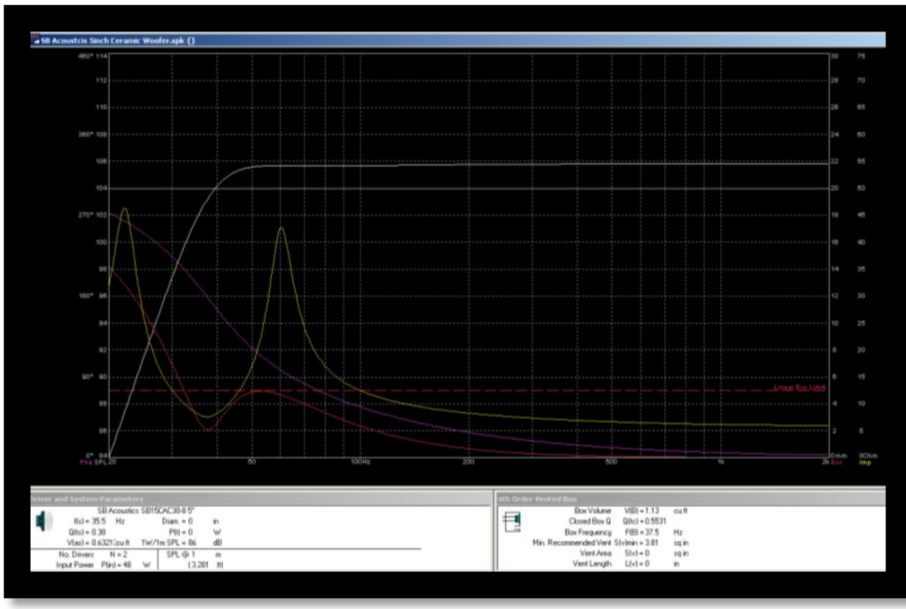
[15] TrueAudio. 2008. *Winspeakerz.* Andersonville.

[16] SB Acoustics. 2010. Accessed February 20th, 2019. *SB Acoustics: 5" SB15NBAC30-4.* http://www.sbacoustics.com/index.php?cID=232

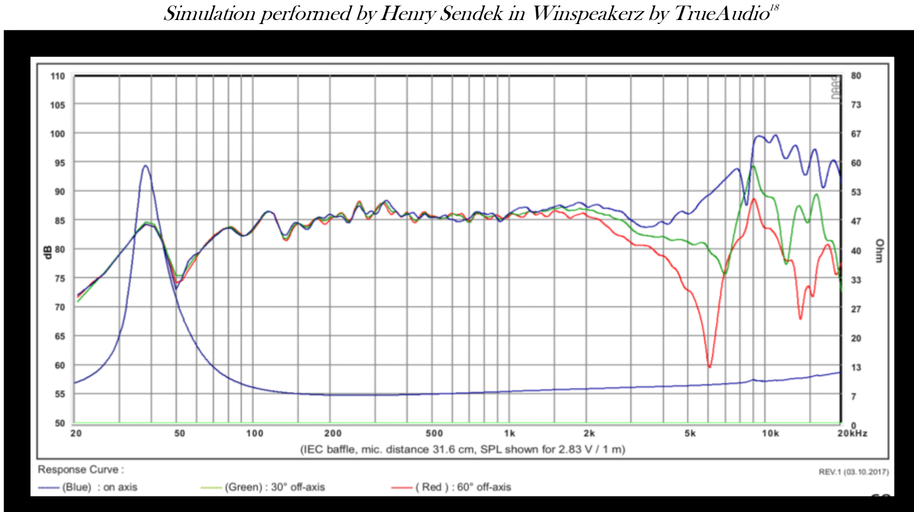
SB Acoustics SB15CAC30-8

5" Ceramic Woofer

I'm a huge fan of the aesthetic of the *Yamaha HS8* loudspeaker. I've been staring at them since my Freshman year of college and they've grown on me considerably since I purchased them. Therefore, once I discovered the ceramic versions of the SB Acoustic's CAC models, I fell in love all over again (although the woven carbon fiber cone may still be my all-time favorite, but sadly, it is not made as a 5" diameter). The eight-ohm version of the woofer posts some impressive specifications: Fs of 35.5Hz, Vas of 17.9liters, relatively low Qts & Qes, but a sensitivity of only 86dB (at 1w at 1m).[17]



Simulation performed by Henry Sendek in Winspeakerz by TrueAudio[18]



Frequency Response Plot taken from SB Acoustics 5" SB15CAC30-8 Spec Sheet[19]

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[17] SB Acoustics. 2010. Accessed February 20th, 2019. *SB Acoustics: 5" SB15CAC30-8.* http://www.sbacoustics.com/index.php?cID=275

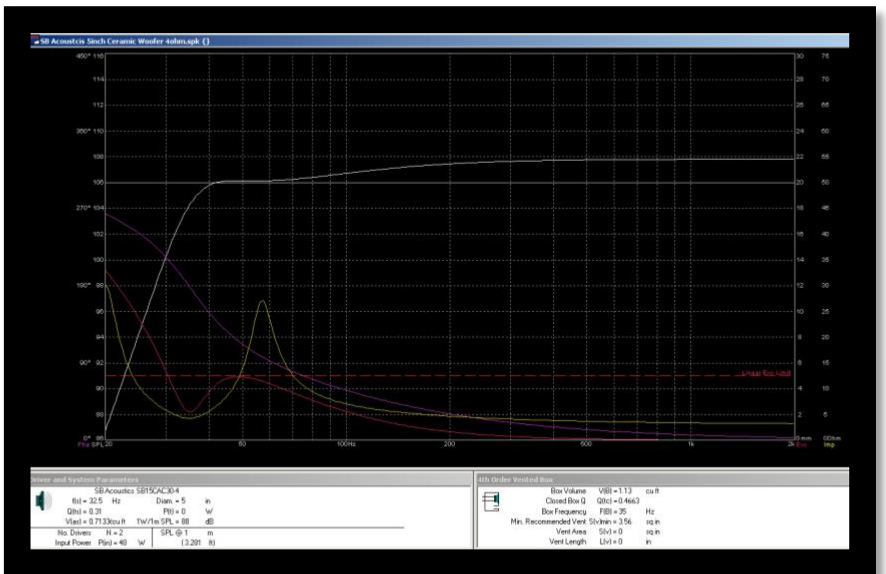
[18] TrueAudio. 2008. *Winspeakerz.* Andersonville.

[19] SB Acoustics. 2010. Accessed February 20th, 2019. *SB Acoustics: 5" SB15CAC30-8.* http://www.sbacoustics.com/index.php?cID=275

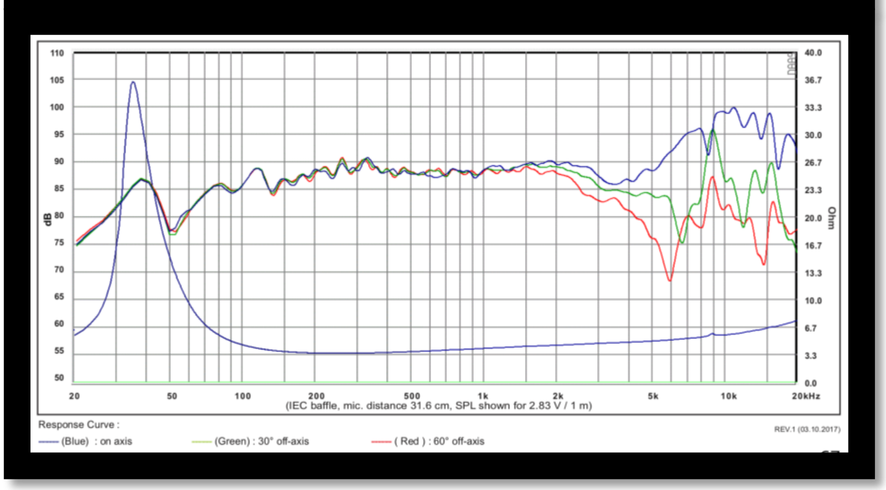
SB Acoustics SB15CAC30-4

5" Ceramic Woofer

After spending multiple days searching for the perfect driver for my loudspeakers, I finally found it. SB Acoustics four-ohm CAC driver has become the ideal fit for my loudspeakers. An Fs of 32.5 combined with a sensitivity of 88dB with an equivalent volume of 20.2liters and an excursion of 5mm was exactly what I needed for my ideal dimensions! The dual woofer setup allows for a 108dB SPL output (with a thermal limit of 106dB) and an F_3 of 36Hz (1Hz lower than the other three drivers). As well, the driver does not begin to distort (due to over-excursion) until 30.5Hz (a significant advantage over the other three drivers).[20]



Simulation performed by Henry Sendek in Winspeakerz by TrueAudio[21]



Frequency Response Plot taken from SB Acoustics 5" SB15CAC30-4 Spec Sheet[22]

[20] SB Acoustics. 2010. Accessed February 20th, 2019. *SB Acoustics: 5" SB15CAC30-4.* http://www.sbacoustics.com/index.php?cID=274

[21] TrueAudio. 2008. *Winspeakerz.* Andersonville.

[22] SB Acoustics. 2010. Accessed February 20th, 2019. *SB Acoustics: 5" SB15CAC30-4.* http://www.sbacoustics.com/index.php?cID=274

Tweeters

Once I decided to go with the *SB Acoustics SB15CAC30-4 5"* driver for my dual mid-woofer design (in an MTM configuration) I needed to chooser a tweeter that would be a good compliment to the high-end frequency response of my woofers. The *SB15CAC30-4* begins to roll off around 2.5kHz and does not begin to climb back up towards the breakup frequency until 5kHz.[23] This would allow for an easy integration with a second or third-order low-pass filter – especially with my choice of active crossovers.

Looking back on my initial design requirements, I realized I needed a tweeter with an extremely wide horizontal dispersion that also has a very flat frequency response throughout the horizontal axis. This will not only allow for a very wide listening area to be covered in any living room, it will also increase the chance of the effects of ASW becoming present and amplifying the quality of sound my loudspeakers produce.[24] Therefore, I have decided to research ribbon tweeters for their high sensitivity to match my SPL requirements for K20 monitoring at 6-meters, for their amazing horizontal off-axis frequency response, and for their vertical off-axis frequency response with a smooth roll-off (to help eliminate any unwanted reflections from hard ceilings & floors).[25]

The two following *Fountek* ribbon tweeters have been chosen because of their impressively smooth frequency responses and their relatively low price point. Other tweeters were considered earlier on in the process, but these are the two tweeters that have stood out most consistently to me.

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[23] SB Acoustics. 2010. Accessed February 20th, 2019. *SB Acoustics: 5" SB15CAC30-4.* http://www.sbacoustics.com/index.php?cID=274

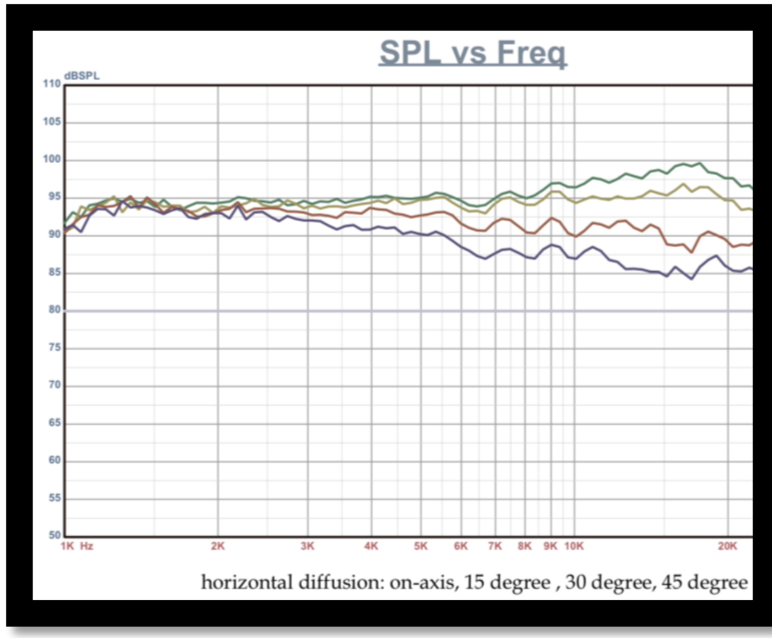
[24] Toole, Floyd E. 2008. *Sound Reproduction: Loudspeakers and Rooms.* Burlington, Massachusetts: Focal Press. 67-71.

[25] (Plummer 2019). 02-18-2019

Fountek NeoCD3.5H True Ribbon Tweeter

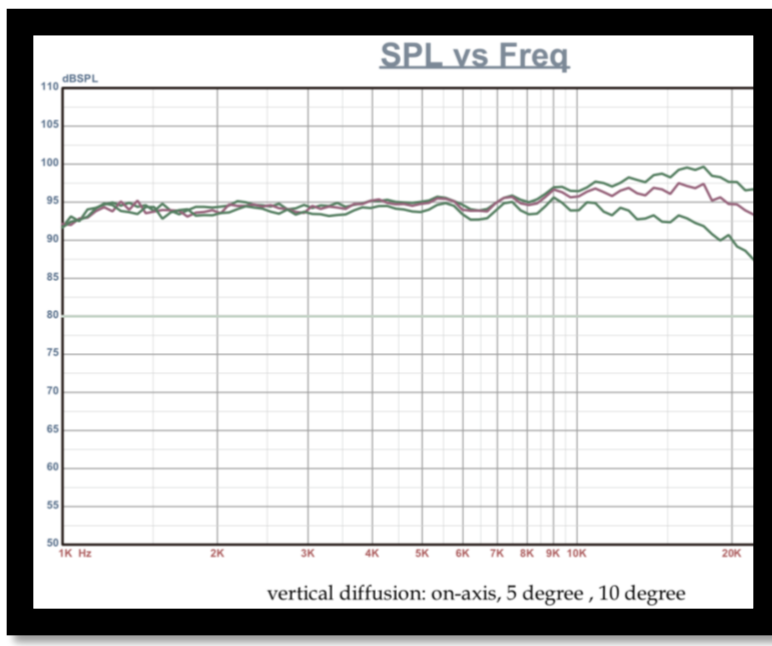
3" Horn-Loaded Ribbon Tweeter

The *NeoCD3.5H* tweeter is truly an impressive invention. The tweeters are able to produce a continuous output of 106dB SPL, which will fit perfectly within the thermal limit of my mid-woofers while only drawing 12W of power.[26] The two following graphs show the on & off-axis frequency response of the tweeters -- the first graph being the horizontal frequency response and the second graph the vertical frequency response. I have cropped the graphs to only show up to, approximately, 22kHz, as *Fountek* supplies a measurement that reaches 40kHz but can easily mislead an uninformed viewer.



Screen shot taken from the NeoCD3.5H spec sheet[27]

As can be seen in the graphs, the *NeoCD3.5H* exhibits a gentle roll-off in both directions (although the horizontal dispersion begins rolling-off around 3kHz while the vertical dispersion holds on until 8kHz). However, I will mostly have the final tuning of my loudspeakers roll-off some of the high end, to give the loudspeakers a "warmer" sound, and this could be inadvertently increased by the amount of frequency roll-off off-axis.



Screen shot taken from the NeoCD3.5H spec sheet[28]

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[26] Fountek. n.d. "NeoCD3.5H Ribbon Tweeter." *Fountek.* Accessed 2 21, 2019. http://www.fountek.net/neocd3.5h.html.

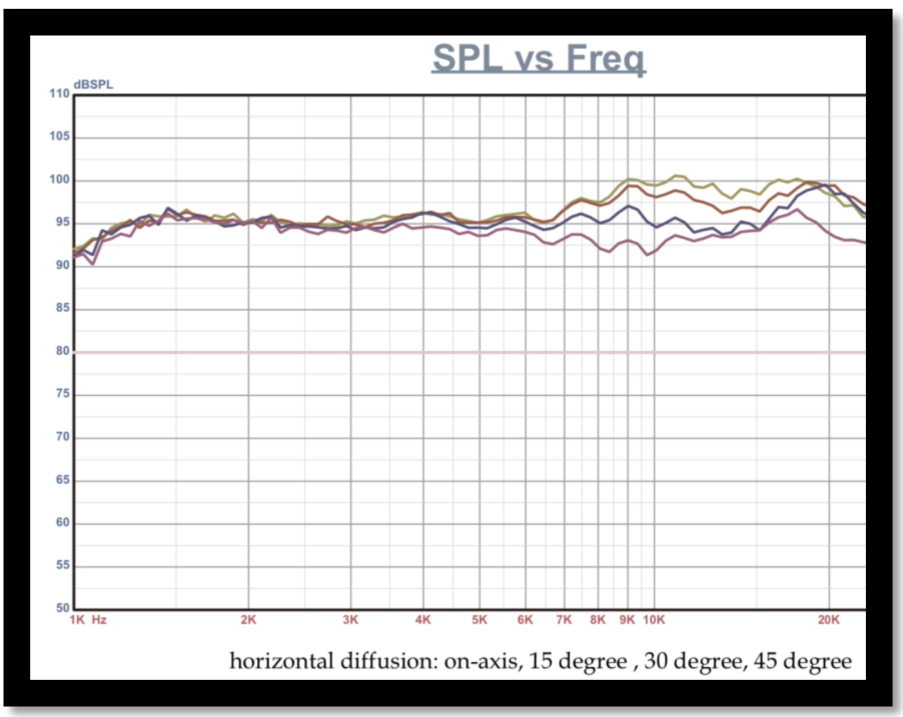
[27] Fountek. n.d. "NeoCD3.5H Ribbon Tweeter." *Fountek.* Accessed 2 21, 2019. http://www.fountek.net/neocd3.5h.html.

[28] Fountek. n.d. "NeoCD3.5H Ribbon Tweeter." *Fountek.* Accessed 2 21, 2019.

Fountek NeoCD2.0 True Ribbon Tweeter

5" Ribbon Tweeter

The *NeoCD2.0* tweeter is another fantastic driver that *Fountek* manufactures. The ribbon is capable of a continuous output of 110dB SPL, with 20W of power and a thermal limit of 114dB SPL -- well above my requirement for the loudspeakers (as well as the output of the mid-woofers).[29] Once again, the two following graphs show the on-axis versus off-axis frequency response in both the horizontal & vertical axes (with the graphs cropped to only show the relevant frequency range).



Screen shot taken from the NeoCD2.0 spec sheet[30]

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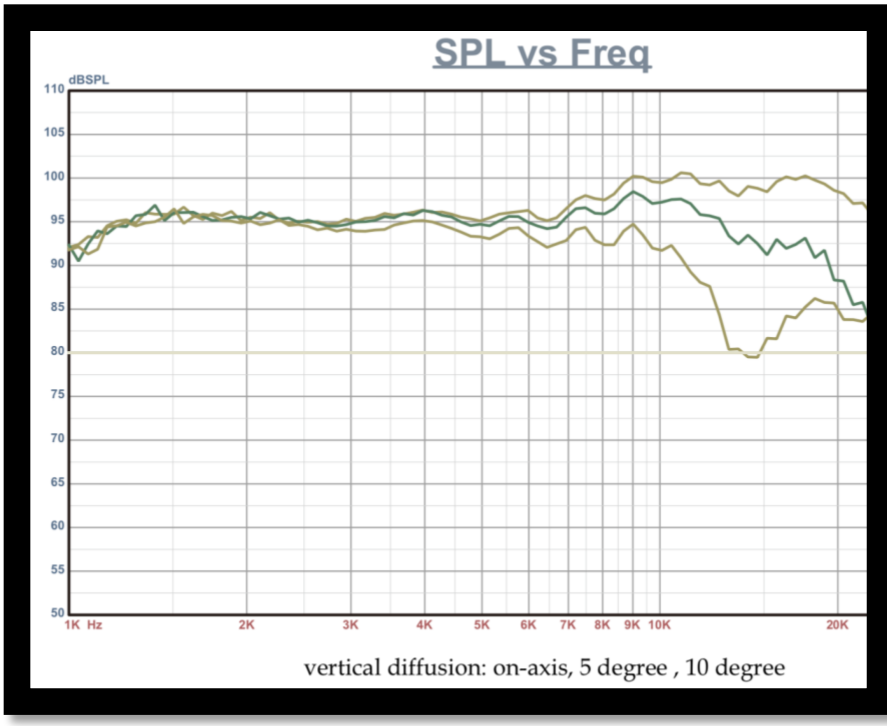
http://www.fountek.net/neocd3.5h.html.

[29] Fountek. n.d. "NeoCD2.0 Fibbon Tweeter." *Fountek.* Accessed 2 21, 2019. http://www.fountek.net/neocd2.0.html.

[30] Fountek. n.d. "NeoCD2.0 Fibbon Tweeter." *Fountek.* Accessed 2 21, 2019. http://www.fountek.net/neocd2.0.html.



Screen shot taken from the NeoCD2.0 spec sheet[31]

As can be seen above, the *NeoCD2.0's* frequency response 45 degrees off center is nearly identical to the frequency response on axis (0 degrees). However, at 10 degrees off-axis above or below the driver, a weird dip in the frequency response occurs just below 15kHz and remains a concern if I were to move forward with this specific tweeter (and is the main reason I have not already committed to this specific driver).

The final factor contributing to my debate over which ribbon tweeter is the "correct" tweeter for my application is the price. The *NeoCD3.5H* costs an incredibly low $57.00 on MadiSound's website while the *NeoCD2.0* comes in at twice the price: $114.00 (on the same website).[32, 33] The ideal tweeter for my loudspeakers would consist of a combination of the two drivers; the horizontal response of the *NeoCD2.0*, the vertical response of the *NeoCD3.5H*, the sensitivity of the *NeoCD2.0*, and the price of the *NeoCD3.5H*. Unfortunately, no such combination exists and I instead will move forward with the *NeoCD2.0* for it's extremely flat off-axis horizontal response.

Enclosure Design

Unfortunately, I have very limited carpentry skills and those that I do possess I tend to overestimate. During some brainstorming sessions early on in the process of developing ideas for

[31] Fountek. n.d. "NeoCD2.0 Fibbon Tweeter." *Fountek.* Accessed 2 21, 2019. http://www.fountek.net/neocd2.0.html.
[32] Madisound Speaker Components, Inc. n.d. *Fountek NeoCd3.5H Horn Tweeter.* Accessed 2 21, 2019. https://www.madisoundspeakerstore.com/ribbon-tweeters/fountek-neocd3.5h-horn-tweeter/.
[33] Madisound Speaker Components, Inc. n.d. *Fountek NeoCd2.0M-blk 5" Ribbon Tweeter.* Accessed 2 21, 2019. https://www.madisoundspeakerstore.com/ribbon-tweeters/fountek-neocd2.0m-blk-5-ribbon-tweeter-rectangular flange-black/.

the aesthetics of my loudspeakers I had sketched some very complex designs. Many of the designs required an excess number of corners and some even required precise curves to be replicated. I quickly realized that if I had any chance of successfully building the cabinets on my own, I would need to stick to simple shapes: cubes and rectangular prisms. Therefore, my main design goals for the *construction* aesthetics of the loudspeakers are to have flush, straight edges with uniform joints. However, I am currently planning to sticker-bomb the sides, top, and rear of the cabinet, while painting the front and bottom baffles with an extremely dark, matte black (these design choices are being held off until I have assembled the cabinets so I can make my designs based off my impressions of the semi-finished product).

The cabinets will be six-sided rectangular prisms with front & rear baffles that are the full height & width of the cabinet. The sides will be the full height of the cabinet, but they will be inset ½" in from the front & rear baffles. The top & bottom baffles with be inset ½" in from all four sides. The woofers & tweeter will be setup in an MTM style, with the top woofer's basket residing approximately one inch below the top of the front baffle (then ½" of space in between the tweeter flange and both woofer baskets). The cabinets will be ported (Bass Reflex) enclosures with the port located on the rear of the cabinet (approximately half a foot above the base of the rear baffle). The port is being placed on the back of the cabinet for both aesthetic & acoustic reasons. I only rarely prefer to see the ports on the front of loudspeakers (and I would much rather have the option to use the port opening as a handle if located on the back of the cabinet). As well, I want to eliminate the amount of reflections that escape the port and reach the listening position(s) while keeping the port within ¼ wavelength of the tuning frequency (roughly 8ft at 36Hz).

The front baffle will have all four of its front edges rounded over with a ½" round over. I will, hopefully, be performing this cut on a router table immediately before gluing the cabinets together. Although this isn't a significant curve to help cut down on edge diffraction, I'm worried that a more significant round over will have an adverse effect on the aesthetics of my loudspeakers. Due to the ultra-wide dispersion of my loudspeakers and the significant listening distance, I am more concerned about the overall aesthetics of the front baffle than the acoustic characteristics (at least to a certain extent – the drivers will definitely be inset/flush mounted to help eliminate some diffraction).

My cabinet design does not account for any time alignment adjust between the tweeter and woofers, nor does it have any type of baffle step correction. I am using active crossovers and so I will be adjusting my driver time alignment & output levels digitally, according to real-world measurements I will taking of the loudspeakers. The main listening access will be directly horizontal to the loudspeakers and therefore they will be tuned & time aligned to accommodate the most accurate frequency response parallel to the horizontal axis. If the real-world scenario requires a different listening axis, the speakers will be physically modified in the space to accommodate the situation (placed on platforms, shims, feet, etc. to angle the loudspeakers).

I will be using a two-layer multiple material construction on all six sides of the enclosure. Each layer will be ½" thick – resulting in inch thick walls on all six sides – and will be glued together prior to assembly. The inner layer of the enclosure will be MDF (medium density fiberboard). The outer layer of the enclosure will be Baltic Birch Plywood (of the highest quality available during purchase). This will be for two reasons: price & acoustic dampening. The MDF is a relatively cheap material and easy to work with, however it is very heavy and quite resonant. Baltic Birch Plywood is a relatively strong wood (which will allow me to round over edges on the front baffle), that is also cheap – but still twice as much as MDF – and significantly lighter than MDF. The two different woods will ideally interact non-linearly when they begin to resonant with the woofers and ideally allow very little mechanical energy to escape the enclosures (as either more mechanical energy or acoustical energy). These assumptions are based on ideas brought forward in the *NorthCreek Cabinet Handbook* as they suggest a composite panel made form MDF, Baltic Birch, and a central, sandwiched, damping layer (however I have omitted the damping layer in my design to best suit my construction ability).[34] I believe that the loudspeakers will be small enough to not require any additional bracing. However, if during the build phase of the project I suspect additional bracing is required, I will add additional layers of wood to the inside of the cabinet as necessary.

I will be inserting high-density, absorbent foam into my cabinet to help reduce cabinet vibrations, cabinet resonances, and reflections from escaping the enclosure. The foam will most likely be placed along the rear baffle and bottom baffle, however the correct amount will be determined across multiple listening sessions with the loudspeakers after they have been appropriately tuned (this is because I do not want to under-stuff or over-stuff the loudspeakers due to the amount of air that may be travelling through the port under certain use conditions). As well, I will attempt multiple listening experiments with fiberglass insulation inside the cabinets to determine if a noticeable improvement occurs with the addition of a secondary damping material.

Finally, I may add some type of feet to the bottom of the loudspeaker. However, I would like to have the option to use the loudspeakers in both the "traditional" position (woofers & tweeter at the top with excess cabinet on the bottom) and the "inverted" position (woofers & tweeter on the bottom and the excess cabinet in the air).

Crossover Design

I will be using an active crossover design for my loudspeakers with individual amplifier channels per loudspeaker driver. I will be using MiniDSP PWR-ICE125 plate amplifiers that have a DSP built into each amplifier. To save space inside my loudspeakers, and cut down on the overall size of the enclosures, I will be mounting the plate amplifiers externally in metal boxes (specifically built by MiniDSP for the amplifiers) and running 4-conductor cables to the speakers.

[34] III, George E. Short. 1992. *North Creek Music Systems Cabinet Handbook*. Old Forge, New York. 7-8.

I am currently designing my loudspeakers to operate as a 2-way system: the two woofers will be wired together (receiving the same signal from the DSP/amplifier) and the tweeter will receive a separate signal from the DSP. However, upon the initial listening sessions with my speakers, I will then decide if I want to switch over to a 2.5-way (one woofer will have a secondary low-pass filter so it only receives the lower half of the frequency range). I am still debating this design because of the results I was able to achieve, with the woofers receiving the identical signal, in the theoretical tests I performed in Winspeakerz.[35]

Ideally, I will be utilizing 2nd or 3rd over filters within my crossover network to have the least amount of impact possible on any phase discrepancies that may arise through the use of extremely steep filters. I will using Butterworth filters as I personally believe that they are the better sounding filter to use in a crossover network (however, this isn't based on any real-world, factual data that I have collected – it's just a strong opinion I have). As well, I have selected my tweeter & woofer combination based around a 2.5kHz crossover point because of the natural roll-off of both drivers. This will aid my crossover circuitry and should allow shallower filters to be applied (with same or similar results).

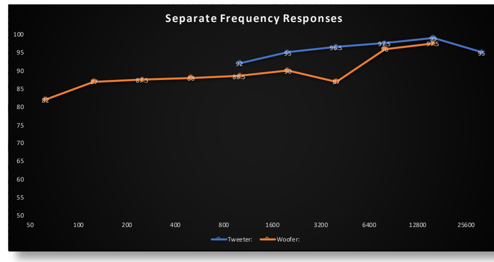
My tweeter is 7dB more sensitive than my woofer. Although my dual-woofer design will allow for an increase in overall sensitivity, I will most likely still need to attenuate my tweeter. This will be easy to do within my DSPs as my tweeters will be on their own DSP output and amplifier channel. However, depending on the overall sound of my loudspeakers, I may choose to have my final tuning not perfectly flat. I have heard certain *Fountek* tweeters that had a "relaxed" or "laidback" sound, especially when compared to a lot of soft dome tweeters. However, I have not yet heard this particular model of ribbon tweeter and will be making my final design decisions after spending a significant amount of time listening to the loudspeakers.

Due to my cabinet design not accounting for time alignment or baffle step corrections, I will be dealing with both of these issues inside the DSPs. This will be quite easy to do as I will be able to adjust the delay, in real-time, in the DSP, while conducting a measurement (with the measurement device in-line with my listening axis) and aligning the phase response of the tweeter & woofer signals. As well, I will easily be able to compensate for baffle step by simply applying a high-shelf filter at the frequency that the effect begins to take place (after taking a frequency response measurement of the loudspeakers).

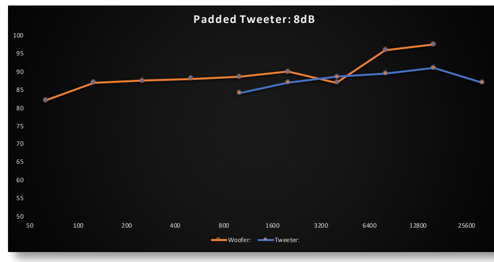
[35] TrueAudio. 2008. *Winspeakerz.* Andersonville.

The image located on the right is a theoretical breakdown of how the crossover between tweeter & woofer will function in my loudspeakers (utilizing the *Fountek NeoCD2.0* and *SB Acoustics SB15CAC30-4*). The first graph shows the factory measured frequency response of the drives, the second graph shows the tweeter with an 8dB attenuation applied, the third graph shows the frequency responses with the corresponding filters applied (filter specs are listened in the title of the graph), and the fourth graph includes the summed frequency response of the two drivers across the frequency range.

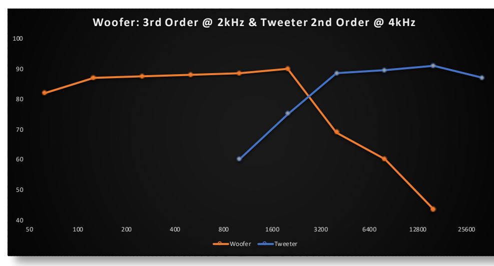
	Woofer:	Tweeter:
Frequency:	SPL:	SPL:
62.5	82	
125	87	
250	87.5	
500	88	
1000	88.5	92
2000	90	95
4000	87	96.5
8000	96	97.5
16000	97.5	99
32000		95



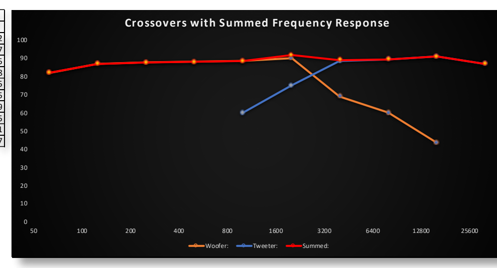
	Woofer:	Tweeter:
Frequency:	SPL:	SPL:
62.5	82	
125	87	
250	87.5	
500	88	
1000	88.5	84
2000	90	87
4000	87	88.5
8000	96	89.5
16000	97.5	91
32000		87



	Woofer:	Tweeter:
Frequency:	SPL:	SPL:
62.5	82	
125	87	
250	87.5	
500	88	
1000	88.5	60
2000	90	75
4000	69	88.5
8000	60	89.5
16000	43.5	91
32000		87



	Woofer:	Tweeter:	Summed:
Frequency:	SPL:	SPL:	SPL:
62.5	82		82
125	87		87
250	87.5		87.5
500	88		88
1000	88.5	60	88.5
2000	90	75	91.75
4000	69	88.5	89
8000	60	89.5	89.5
16000	43.5	91	91
32000		87	87



Construction

Planned Techniques & Finishing

I will be using rabbet joints at every corner of my cabinets to improve both overall strength & rigidity, as well as to decrease the chance of any air gaps along the seams. I will be cutting out each layer of my material (plywood & MDF) to the size that it needs to be for my final design. I will route-out all holes (for drivers, ports & connectors) on the front and rear baffles on the X-Carve CNC at The Alley Makerspace. I will then glue together my interior MDF layers to create my "inner box" to make sure that I eliminate any air gaps or weird alignments. Afterwards (after the interior box has had roughly 24hrs to dry), I will glue my exterior plywood layers over the MDF, interior, box – to once again eliminate as many air gaps and misalignments as possible. Then, finally, I will round over the front edges of my front baffles with a ¼" to ½" round over. I am choosing to cut my wood to the exact size before gluing (rather than using a dado blade on table saw or router after gluing the two separate materials together) because I believe that I can make a more precise cut with a regular table saw blade than I can with a dado blade on the table saw (I have experience using the table saw with a dado blade for a class project and I was not able to maintain a consistent across the, roughly, 200 cuts I made).

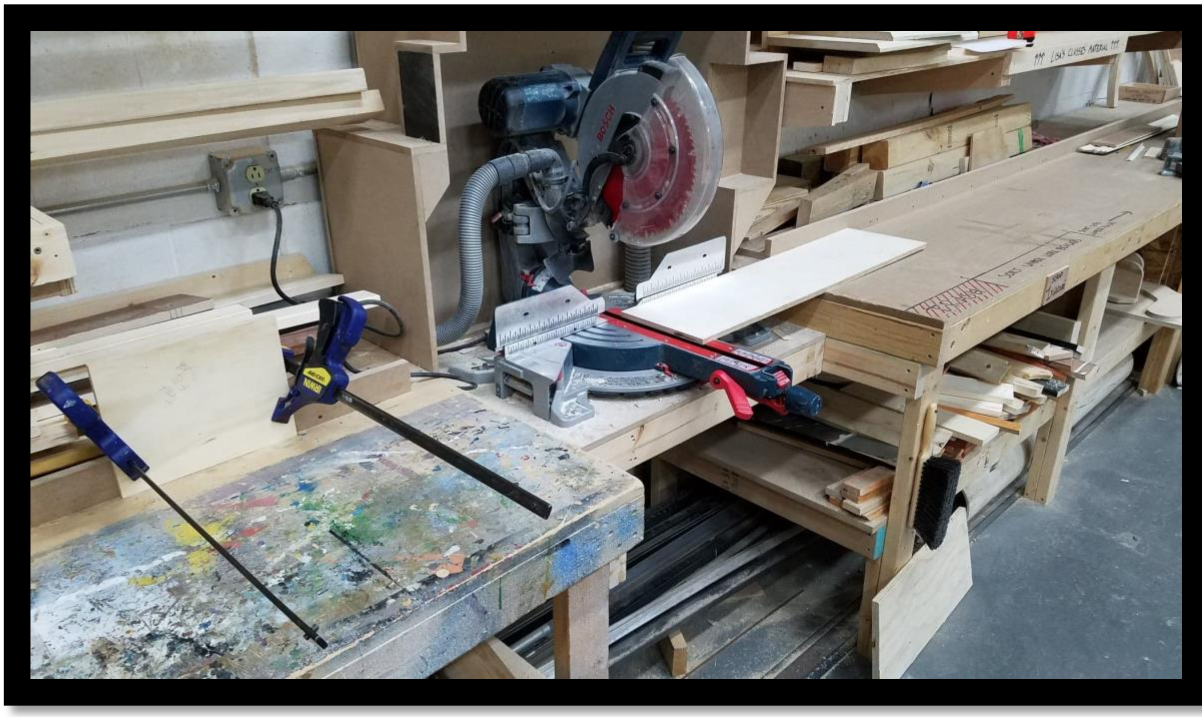
I have drafted out 2-D & 3-D versions of my loudspeakers in advance and dimensioned the appropriate drawings. I will have paper versions of the drafting/construction plans with me the whole time during the build process. This is to ensure that I never forget and/or miss a step, and it will allow me to document any changes that I make to the process. In addition, I have already constructed a cardboard version of one of the cabinets to check the real-world size of the enclosure.

I currently plan to finish my speakers with a unique design that is both functional and aesthetically pleasing. I will be painting the front baffle of the cabinets with an extremely dark, matte black paint. The sides, top & bottom, and rear of the loudspeakers will be clear-coated and then sticker-bombed, before being clear-coated again. The stickers will be covering the entire surface of the plywood; therefore, no plywood will be seen anywhere on the enclosure. I will not fully commit to the idea, however, until I see the enclosure after they have been constructed.

Cabinet Construction

I began the process of constructing the cabinets by laying out a plan (a cut sheet) for my two sheets of wood. I discussed my strategy for tackling all of the cuts as precisely as possible with the Scene Shop Supervisor, *Andrew Nyberg*, who suggested I change a few pieces of my order of events to better suit the project and my skill level. I began by cutting my 4’x8’ sections of wood into the correct widths on the table saw: two strips for the front & rear baffles and two strips for the side baffles. I then to cut the strips down to their required lengths on the miter saw, using a stop-block to ensure all of my pieces would be the exact same length. After this stage of the process, all of my cut pieces were at the correct lengths & widths - with the exception of my top & bottom baffles. I then reset the table saw and trimmed down the top & bottom baffles to their desired lengths. The following group of photos breaks down my process:

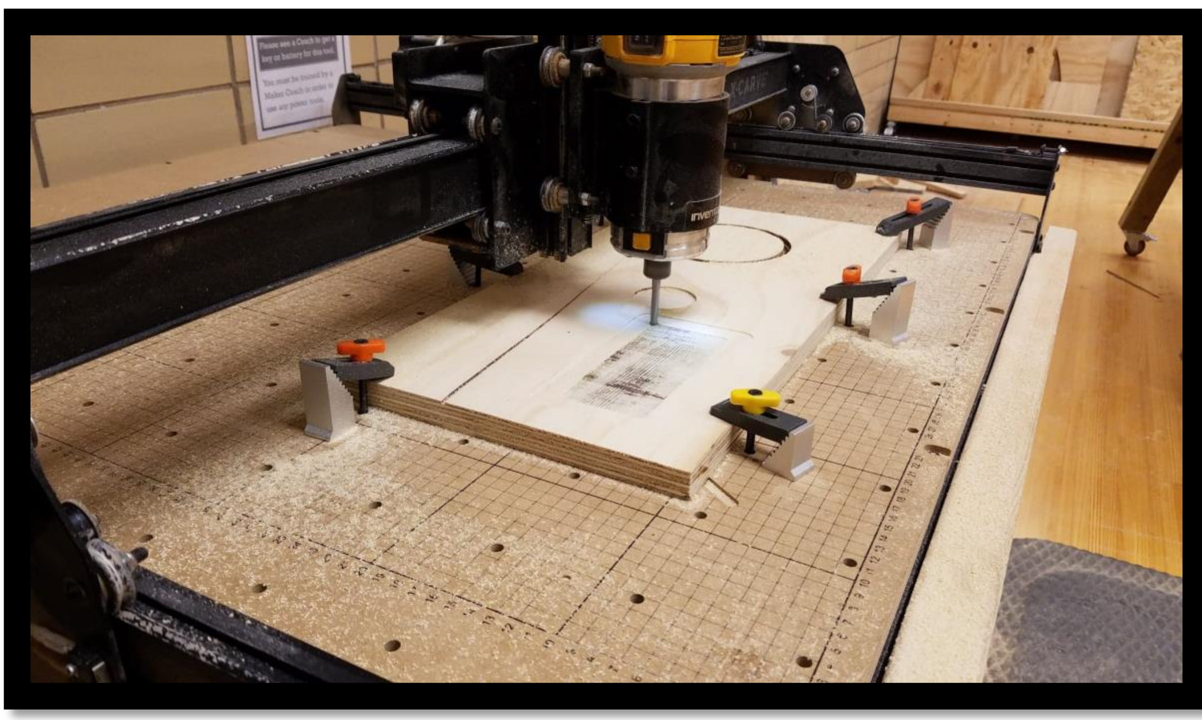
MDF & Plywood 4’x8’ sheets after being run through the table saw



Plywood board after being cut on the miter saw

Plywood & MDF boxes assembled separately to check for any mis-cuts

Plywood & MDF boxes assembled together to check for any size issues



X-Carve CNC running a test cut for the tweeter inset depth

MDF interior boxes glued & clamped

Exterior Baltic Birch layers glued & clamped along with Baltic Birch loudspeaker stand clamped

The above picture on the left is my fully constructed enclosure immediately after the box was finished gluing
The above picture on the right is the same enclosure after installing my drivers in their test positions

Due to some rushed parts of the gluing process, multiple outer edges of the Baltic Birch had open seams. I taped along these seems and filled with latex wood. After the paste had dried, I removed the tape to leave just enough latex wood to have complete filled the seams

The front edges of the loudspeakers were masked so the front baffle could be painted an extremely dark matte black. Unfortunately, time did not allow for the rest of the cabinets to be stained while this paper was being written.

System Tuning

Overview

All of the tuning for my loudspeakers occurred in McArdle Theater at Michigan Tech. McArdle Theater is a large enough space that I will be able to place the loudspeakers on a tall stand to avoid and/or delay any floor reflections and eliminate any boundary effects. As well, this will help distinguish the "sound" of my loudspeakers from the "sound" of the room (as a result from the room reflections occurring much later in time because of the size of the space).

My loudspeakers were designed for use in a living room, next to a large television. The listening axis for these loudspeakers should be perpendicular to the front baffle, centered on the tweeter. Since the ribbon tweeters have such a wide dispersion pattern, this will allow the listening axis to be anywhere along a horizontal plane. However, for the context of this project, all major tuning decisions will assume that the listener will be directly in front of the loudspeakers (as well as being perpendicular to the tweeters).

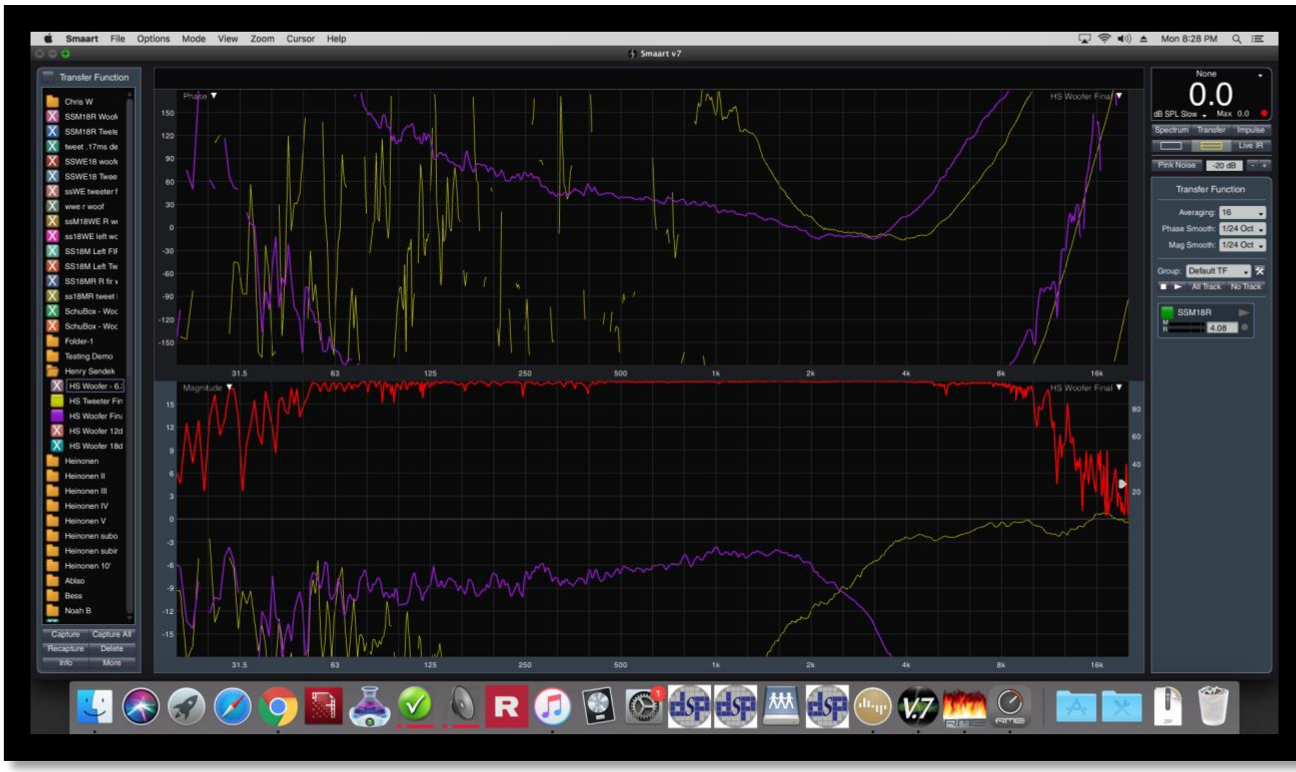
Although it is not a design goal of my loudspeakers for them to meet the K20 standards for mixing (83dB with 20dB of headroom at 1 meter), all of my tuning will occur at 83dB with the measurement microphone located 1 meter from the tweeter.[36] This way, my measurements will all have a standard reference value so I can compare measurements across multiple testing sessions. As well, I will be able to directly compare my measurements against the measurements of my classmates (who will also be measuring at 83dB at a distance of 1 meter).

Loudspeaker measurements will be taken in the software: FuzzMeasure (with the exception of Driver Alignment discussed in the next section).[37] FuzzMeasure will be used to run two second (in length) sine sweeps through the loudspeakers and average three measurements together for every test (to eliminate any nuances or minor differences between individual measurements). This is key because I plan on not having a perfectly quiet testing environment for a majority of my tests due to space availability, space utilization, and the large number of students enrolled in the course.

[36] Katz, Bob. 2000. "Level Practices." *Digital Domain.* Accessed 2, 6, 2019. www.digido.com. 6-7.
[37] RodeTest. 2019. *FuzzMeasure*. Sydney.

Driver Alignment

I began my initial testing by phase-aligning my drivers using the software SMAART; an FFT-based analysis software made by Rational Acoustics, often used in the tuning of sound systems.[38] Due to my 2.5way loudspeaker design, I delayed my tweeter to match the phase of the two woofers to allow for the smoothest crossover. Because my two woofers are driven from the same amp channel, I do not have the ability to digitally delay one driver and not the other. However, because both drivers are mounted into the front baffle with identical depths (and my listening axis is occurring perpendicular to my tweeter that is in the exact middle of the two woofers), this will not be an issue.

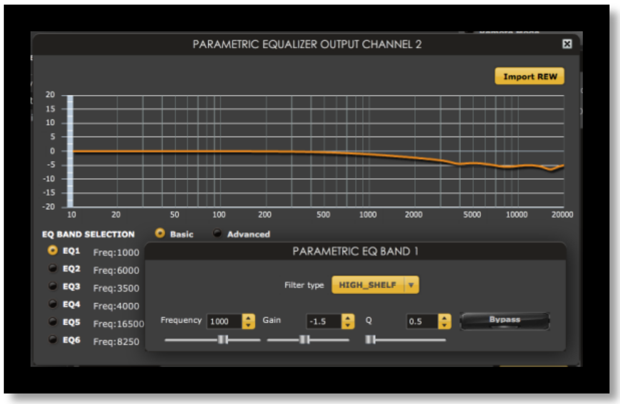


SMAART: Phase Alignment between Woofers & Tweeter

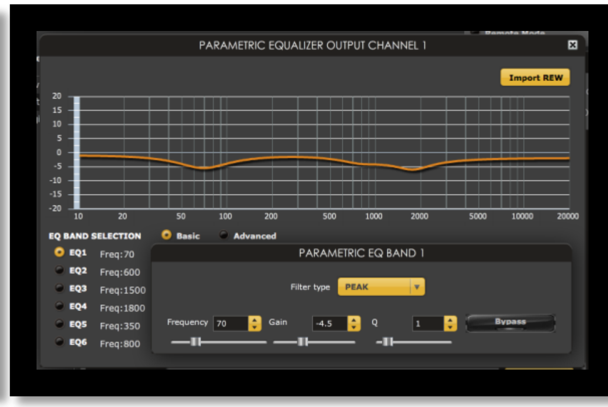
[38] RationalAcoustics. 2019. *SMAART.* Woodstock.

Frequency Measurements

I began my tuning by doing an initial measurement of my tweeter (alone), my woofers (alone), and then a sweep of the full loudspeaker. I then began to level the tweeter to the same level as the woofers by adjusting the amplifier output in my DSP (MiniDSP PWR Ice) units. After leveling the output of both the tweeter and woofers so they were roughly equal, I began to make small adjustments, with Parametric EQ filters (in the DSP software), and record a measurement after each adjustment. This way I was able to immediately see the effect that my adjustment was having on the frequency response and either make a bigger change, make a smaller change, or move on to the next area.

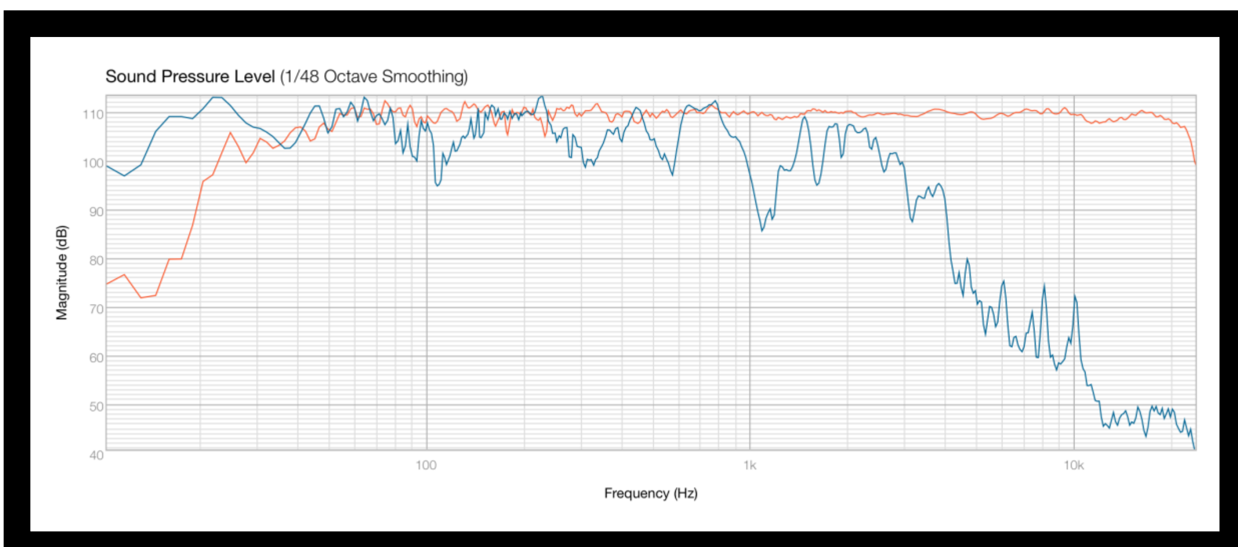


MiniDSP: Final Tweeter EQ

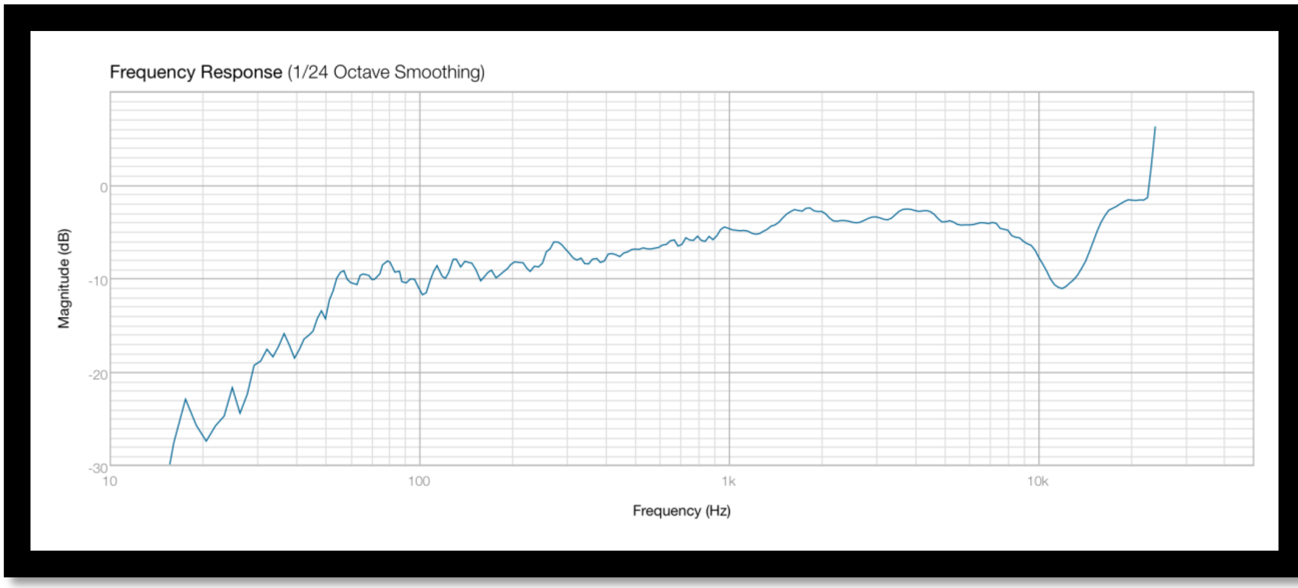


MiniDSP: Final Woofers EQ

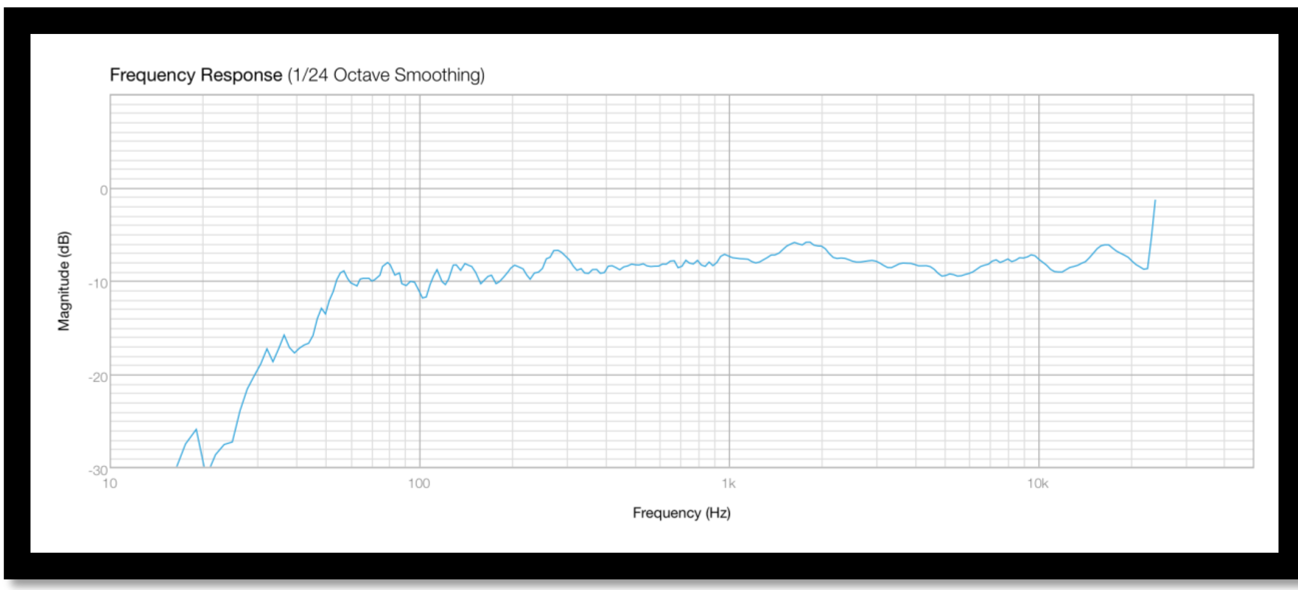
After my initial listening sessions, I decided to commit to a full 2.5way design (crossing over my second woofer at a significantly lower frequency with the use of a single inductor). I chose to utilize a 6.0mH iron-core inductor that would give me a first-order high frequency roll-off starting just above 100Hz. As well, the loudspeakers were tested and listened to with various length ports, before committing to a length of, just over, four inches. The port tuning was measured and deemed suitable for the amount of low frequency extension it provided.



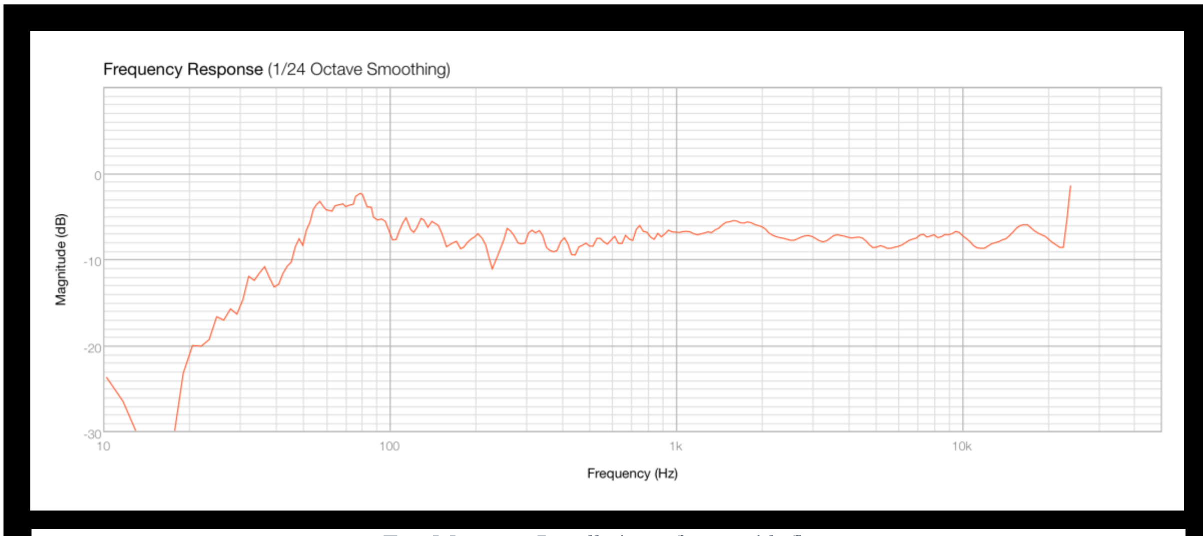
FuzzMeasure: Loudspeaker Frequency Response in Red; Port Frequency Response in Blue



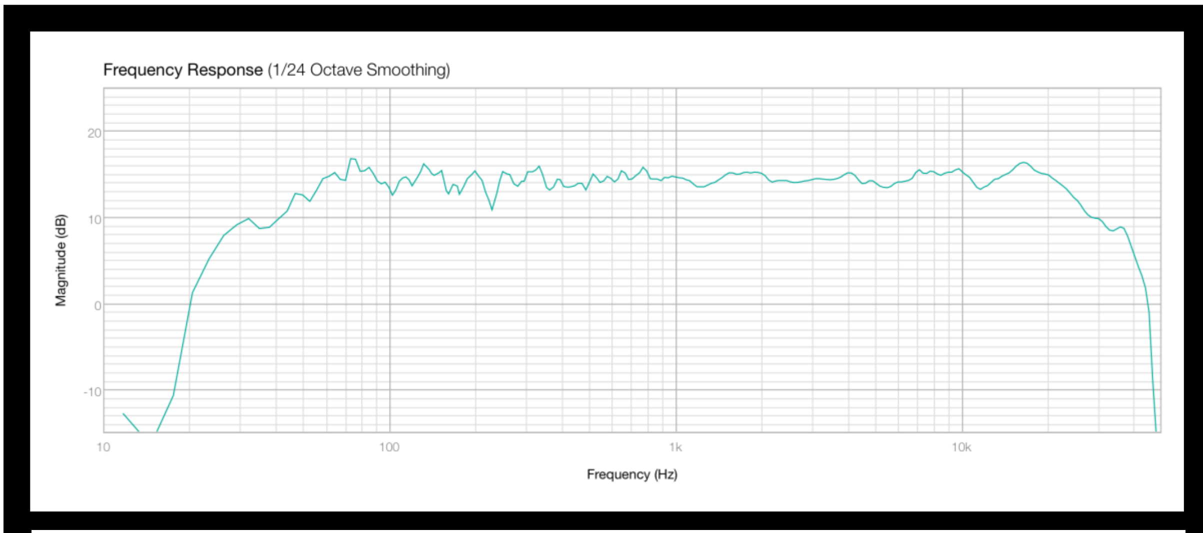
FuzzMeasure: Initial measurement after SMAART alignment & crossover tweaking



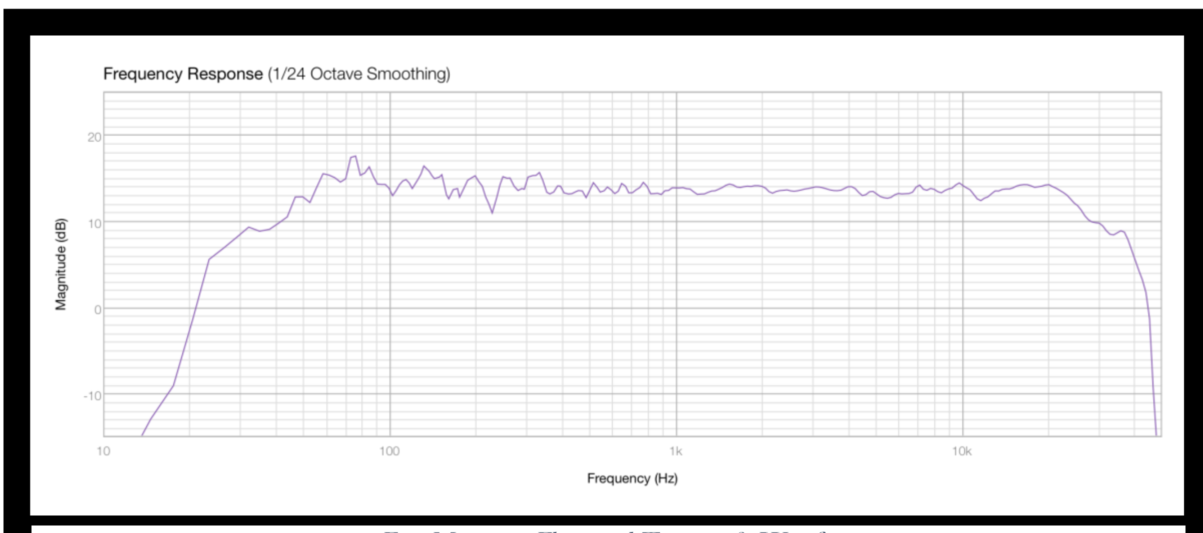
FuzzMeasure: Balanced Woofer & Tweeter



FuzzMeasure: Installation of port with flares



FuzzMeasure: Final Port Length



FuzzMeasure: Flattened Tweeter & Woofer

Dampening Material

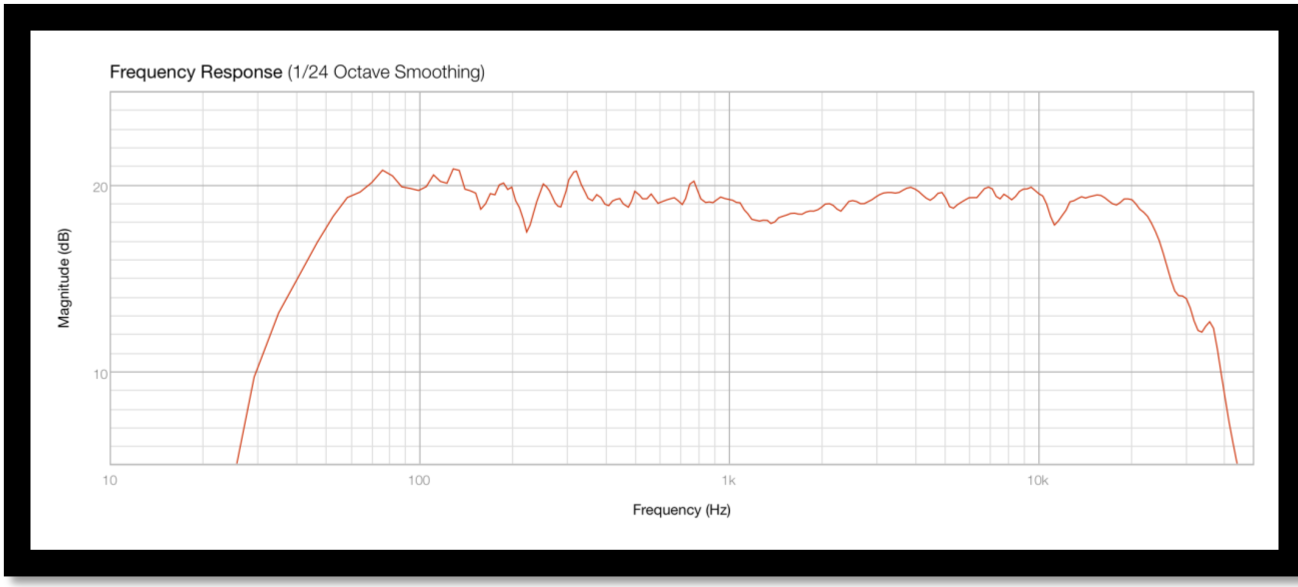
Typically, it is advised that paper-backed fiberglass insulation is used as dampening material inside of loudspeakers.[39] However, I have a distinct desire to not fill my loudspeakers with a material that is that difficult to work with. I opted to purchase eggshell acoustic foam and 3-layer acoustic dampening foam. I performed multiple listening experiments to determine the proper amount of dampening material and found that it was a combination of the two different products. I finalized my plans by using a strip of 3-layer dampening foam, running from the top to just above the port flare, on the inside of my rear baffle. I then placed square cutouts, approximately 6” in height and width, of the eggshell foam directly behind the woofers and glued them to the 3-layer dampening foam. This combination produced the greatest decrease in internal reflections while allowing the maximum amount of stereo image width and depth (two things that are extremely important to my listening experience).

[39] Plummer, Christopher. 2019. "Transducer Theory." 01-04.

Final Performance Documentation

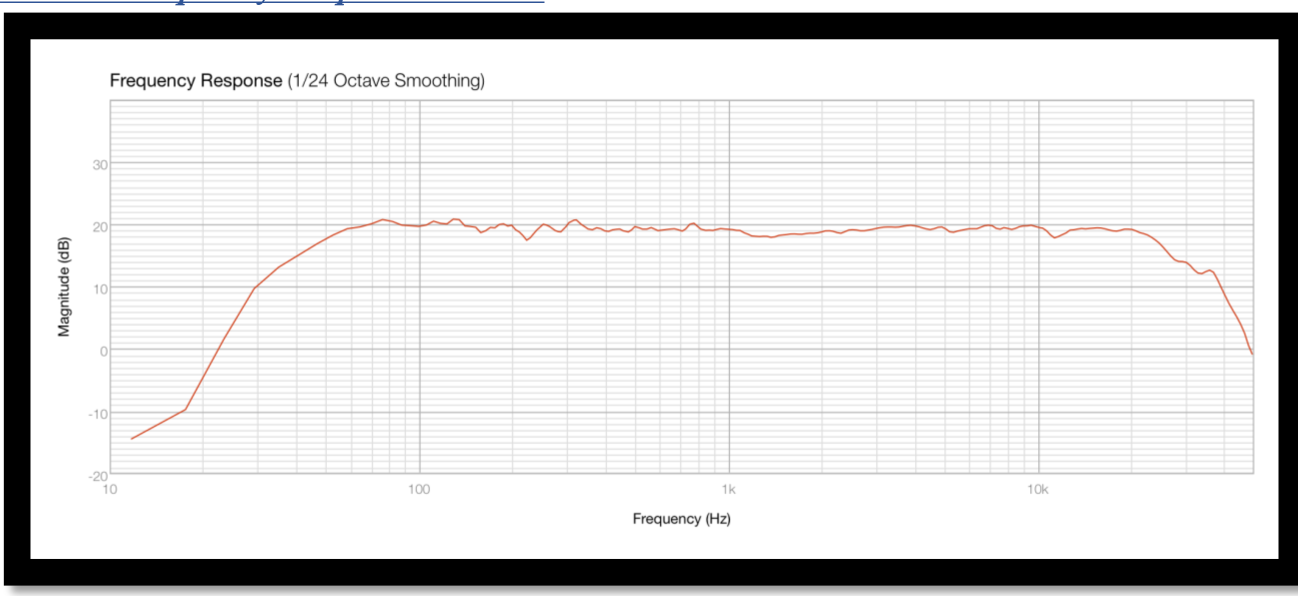
Below are the compiled graphs from the final testing of my loudspeakers. Each graph is accompanied with a caption that briefly describes the test and what it is measuring.

Overall Frequency Response – 20dB



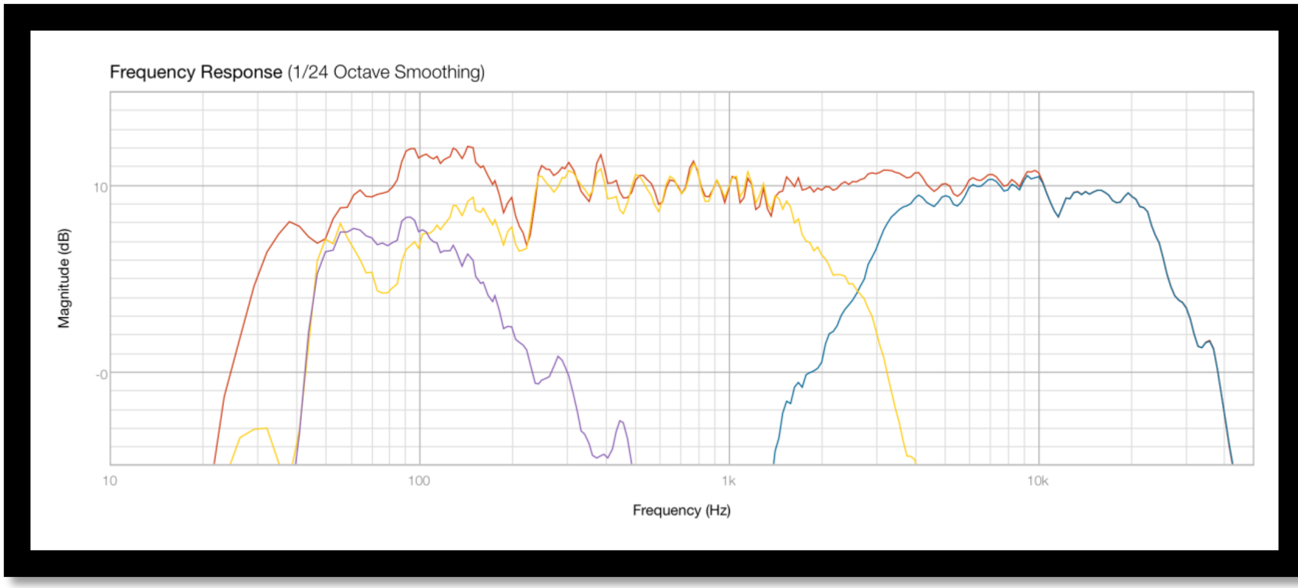
Overall Frequency Response measured at ½ meters at 89dB

Overall Frequency Response – 60dB



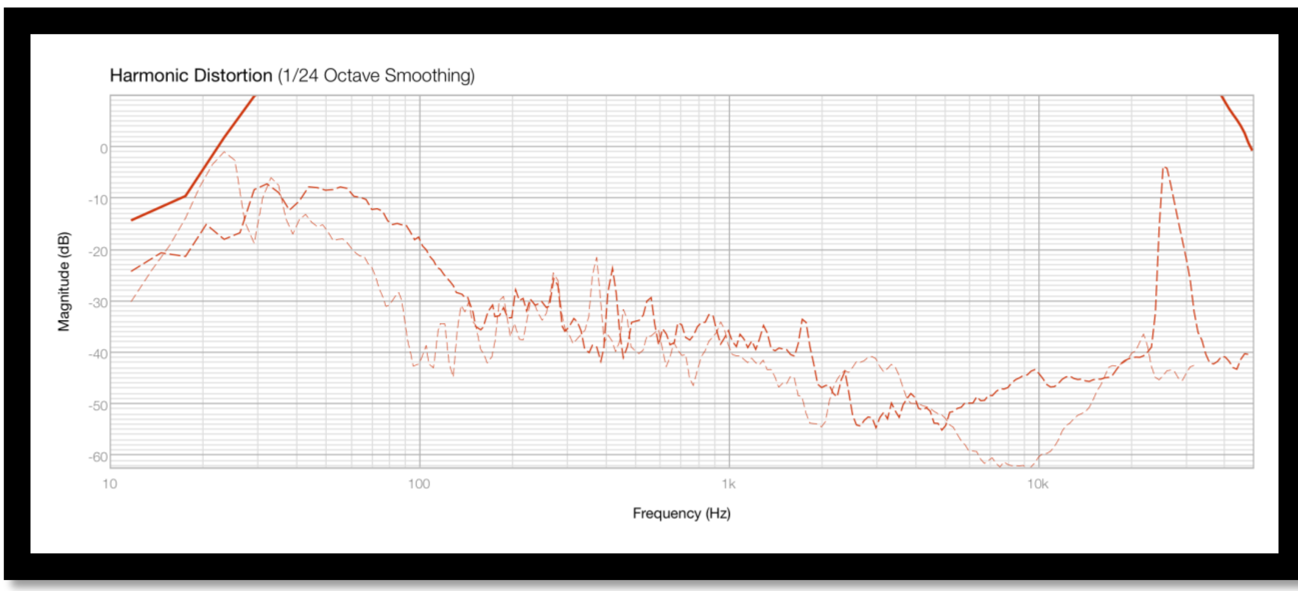
Overall Frequency Response measured at ½ meter at 89dB

Driver Frequency Response



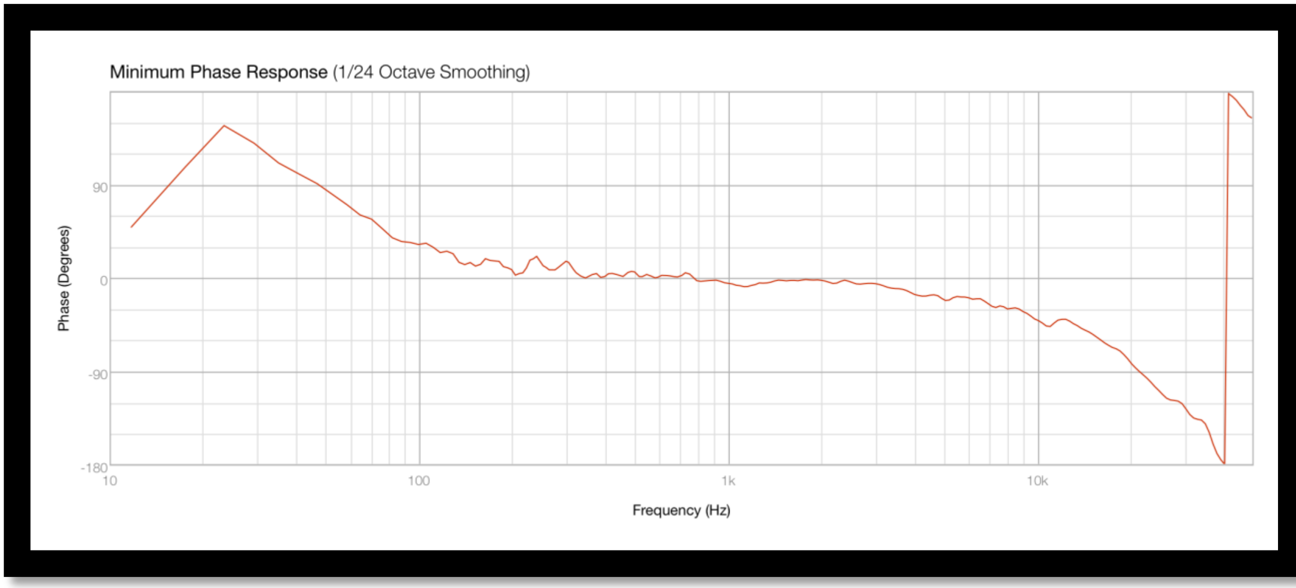
Integrated Driver Frequency Response measured at ½ meter at 89dB
Red: Full Loudspeaker, Blue: Tweeter, Yellow: Top Woofer, & Purple: Bottom Woofer

Harmonic Distortion



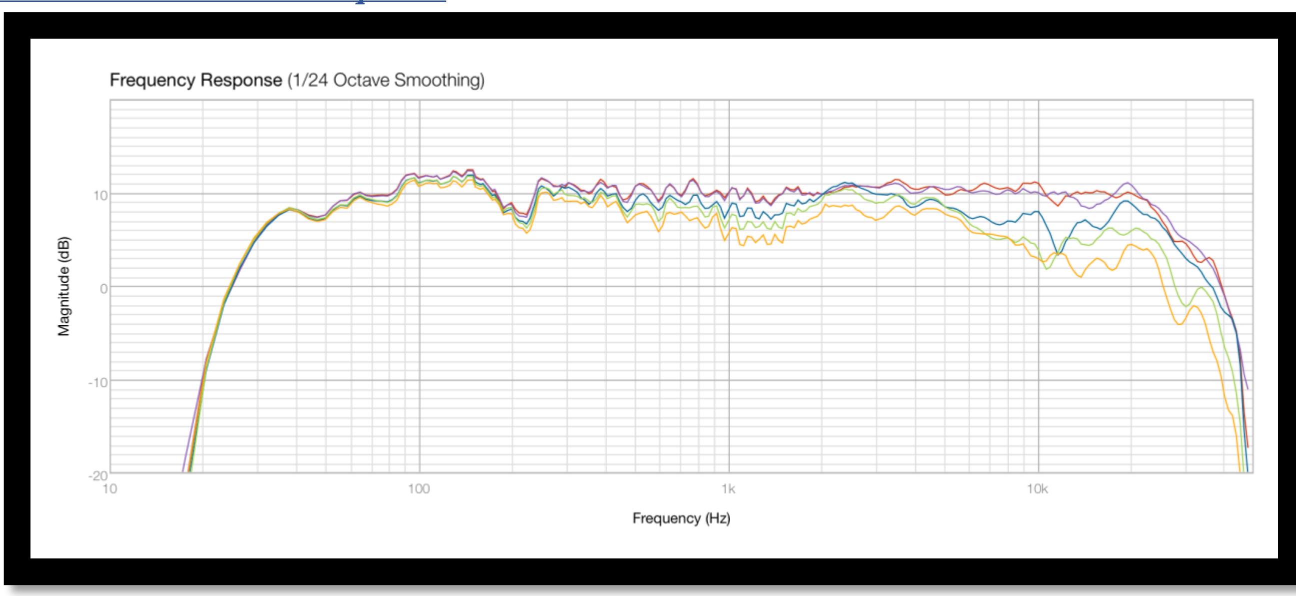
Harmonic Distortion Response measured at ½ meter at 89dB

Minimum Phase



Minimum Phase Response measured at ½ meter at 89dB

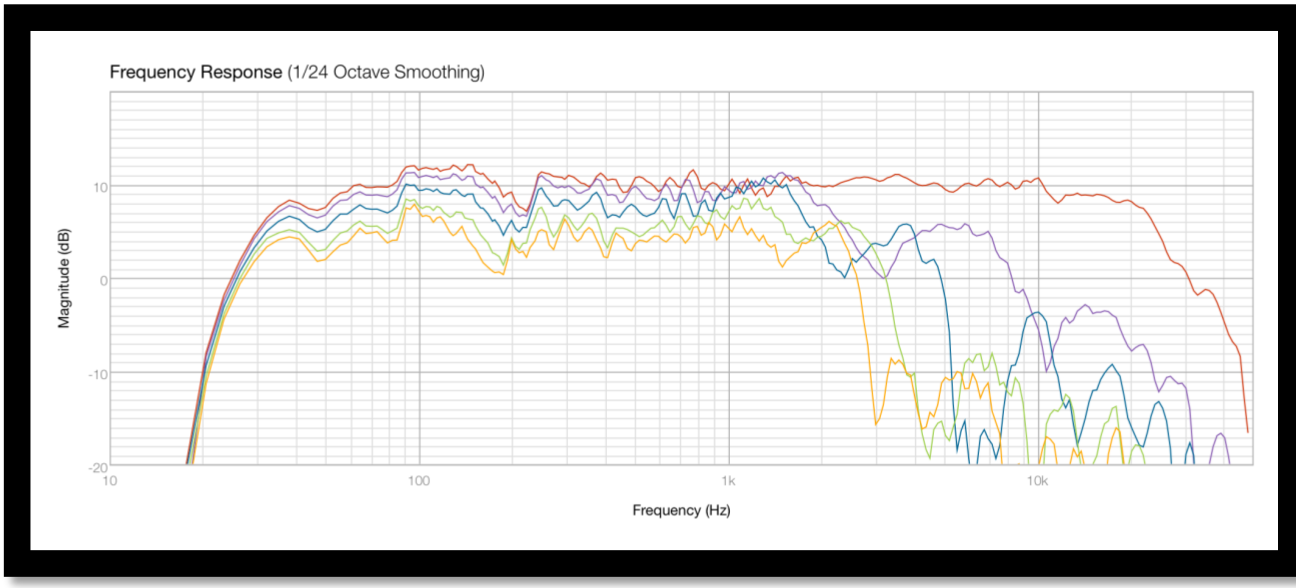
Horizontal Off-Axis Response



Frequency Response measured on axis (Red) & off axis at 15° (Purple), 30° (Blue), 45° (Green), and 60° (Orange) [measured at ½ meter at 89dB]

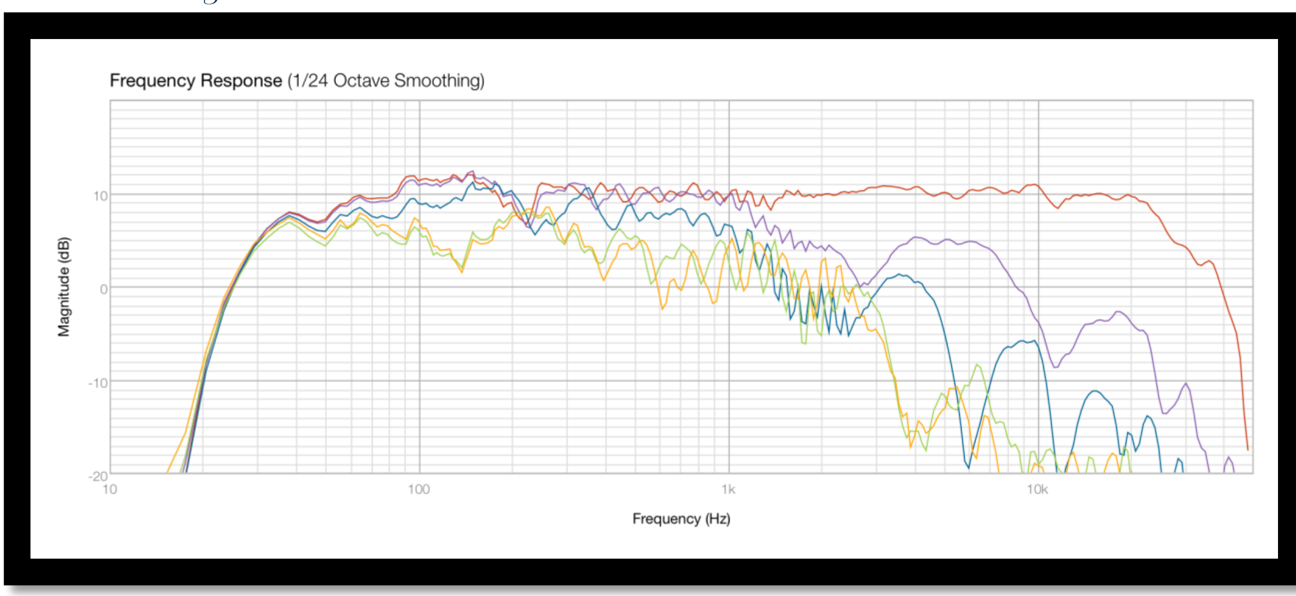
Vertical Off-Axis Response

Above Listening Axis



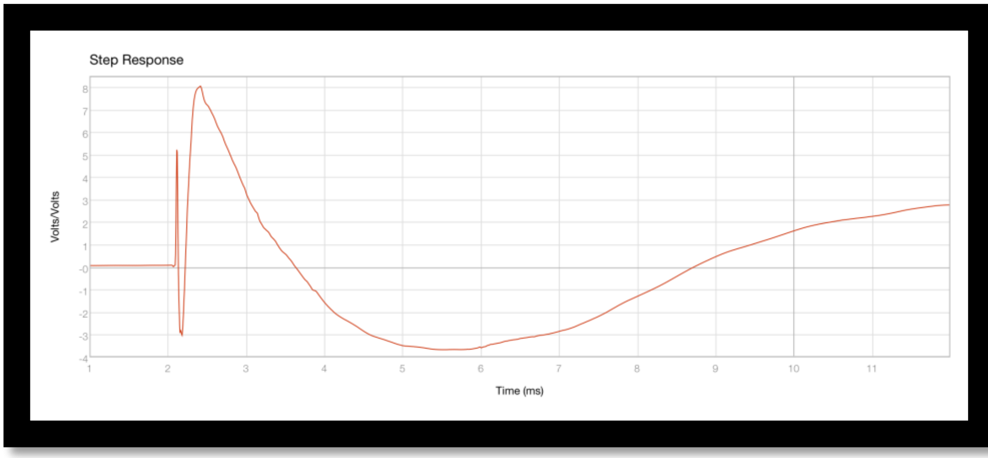
Frequency Response measured on axis (Red) & off axis at 15° (Purple), 30° (Blue), 45° (Green), and 60° (Orange) [measured at ½ meters at 89dB]

Below Listening Axis



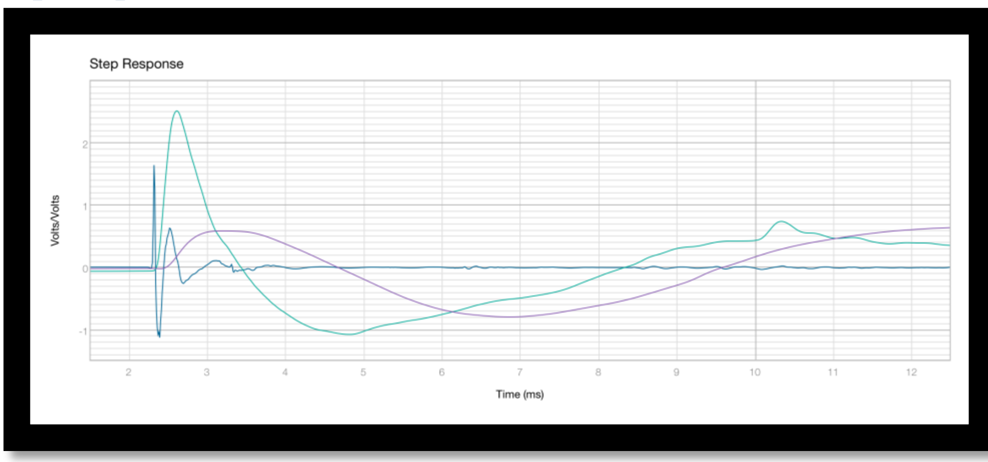
Frequency Response measured on axis (Red) & off axis at 15° (Purple), 30° (Blue), 45° (Green), and 60° (Orange) [measured at ½ meters at 89dB]

Step Response



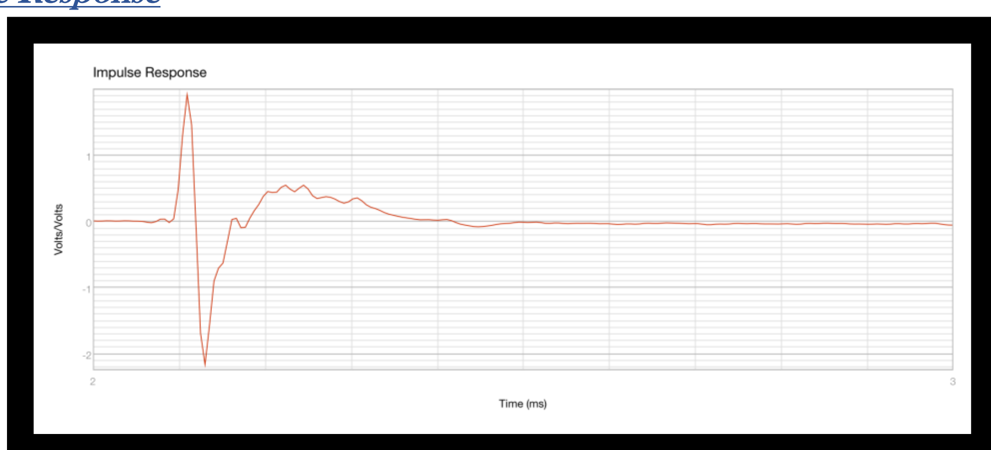
Step Response measured at ½ meter at 89dB

Driver Step Response



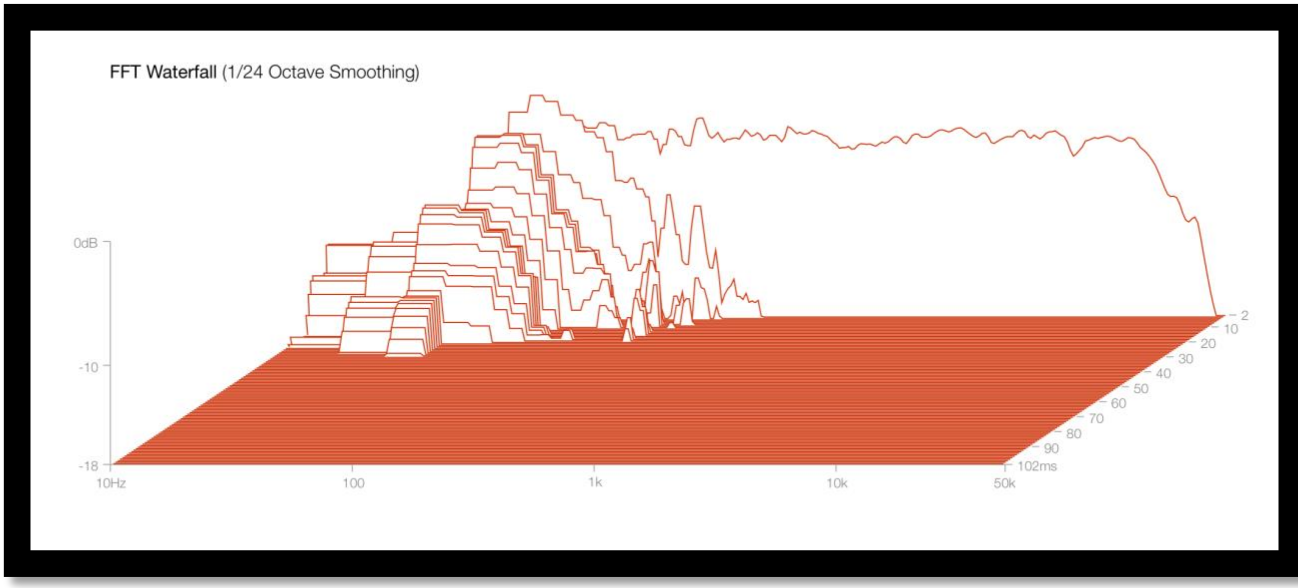
Integrated Step Response of each driver measured at ½ meter at 89dB;
Blue: Tweeter, Green: Top Woofer, & Purple: Bottom Woofer

Impulse Response



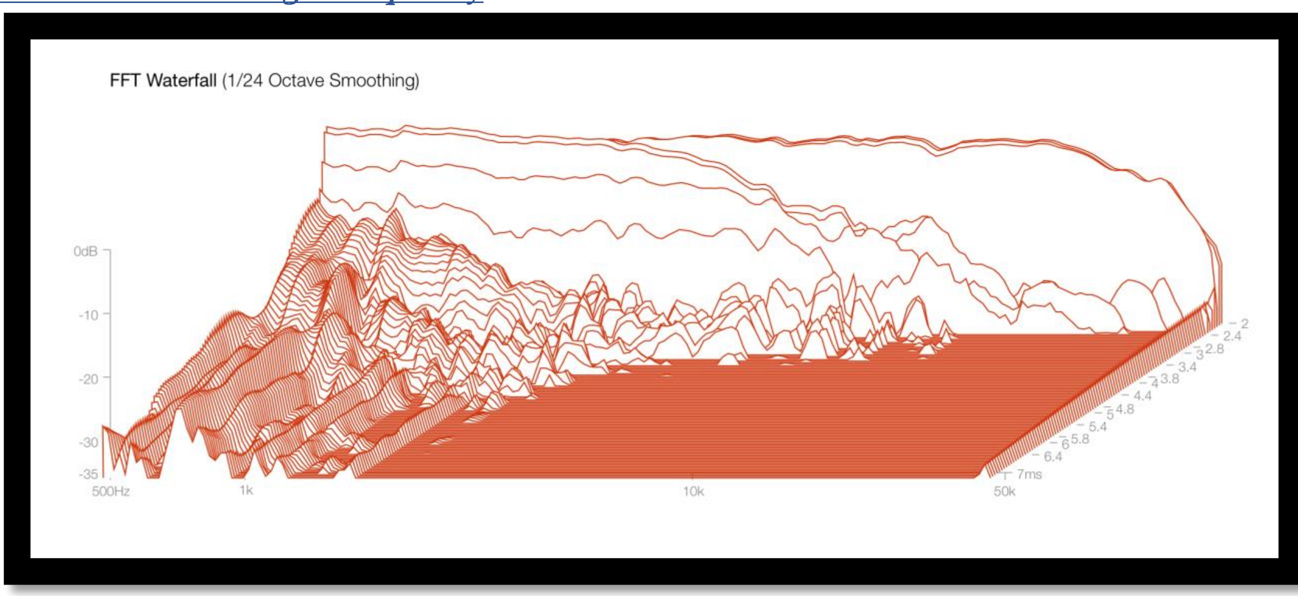
Impulse Response measured at ½ meter at 89dB

Waterfall Plot – Full



Waterfall Plot: 10Hz to 50kHz measured at ½ meter at 89dB

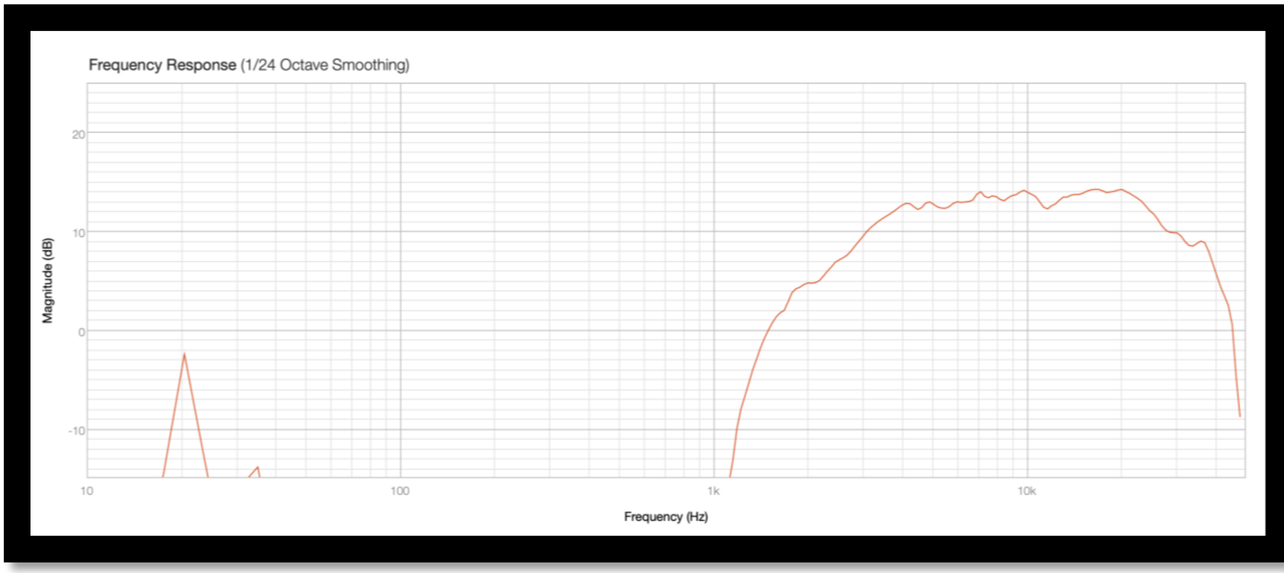
Waterfall Plot – High Frequency



Waterfall Plot: 500Hz to 50kHz measured at ½ meter at 89dB

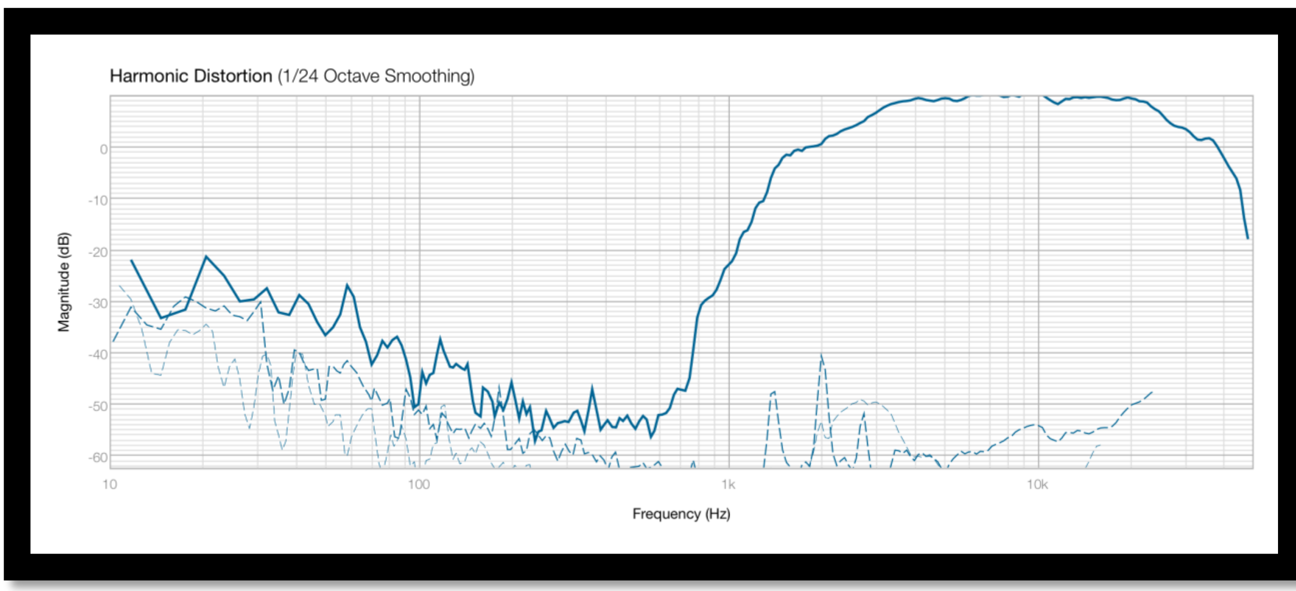
Driver Responses – Tweeter

Frequency Response



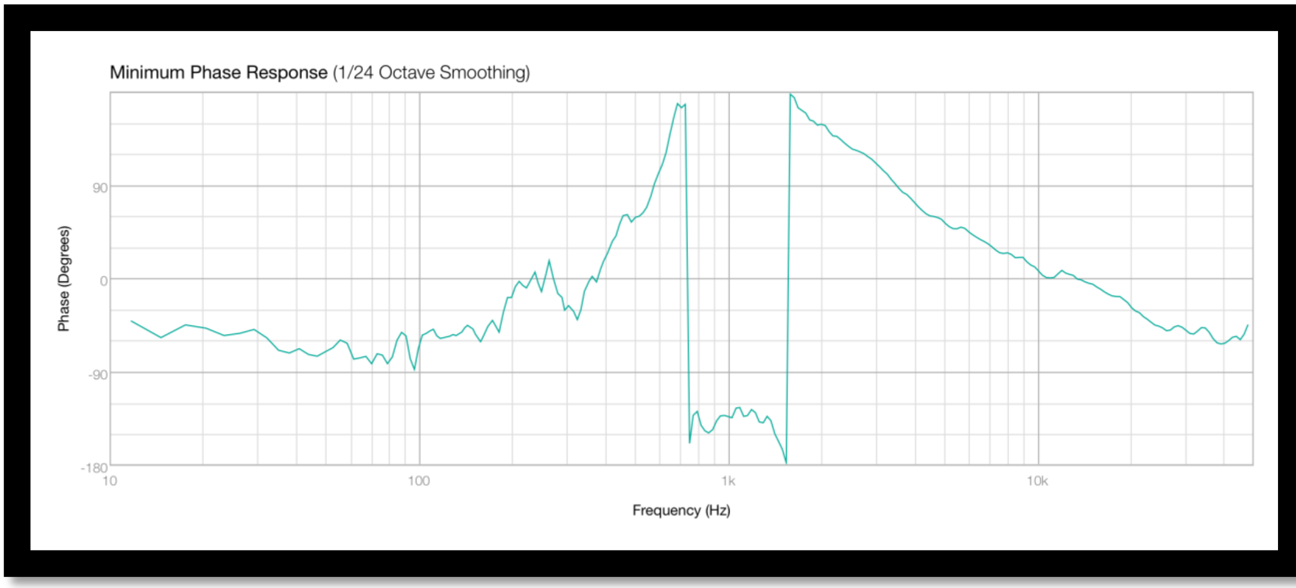
Tweeter Frequency Response measured at ½ meter at 89dB

Harmonic Distortion



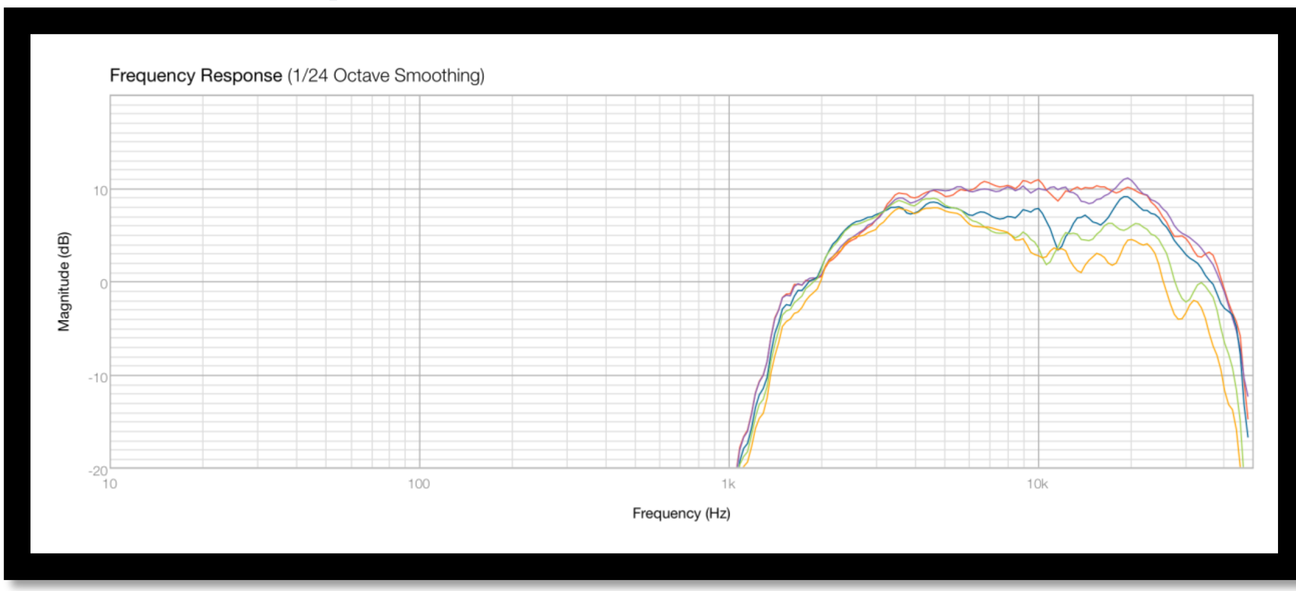
Tweeter Harmonic Distortion Response measured at ½ at 89dB

Minimum Phase



Tweeter Minimum Phase Response measured at ½ meter at 89dB

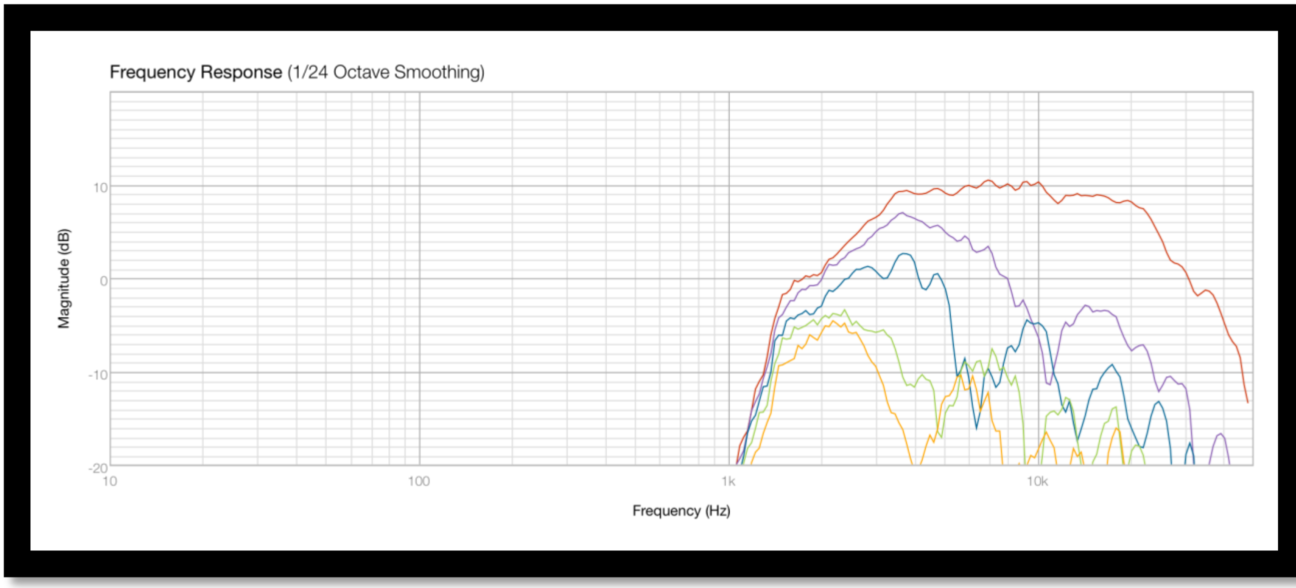
Horizontal Off-Axis Response



Frequency Response measured on axis (Red) & off axis at 15° (Purple), 30° (Blue), 45° (Green), and 60° (Orange) [measured at ½ meter at 89dB]

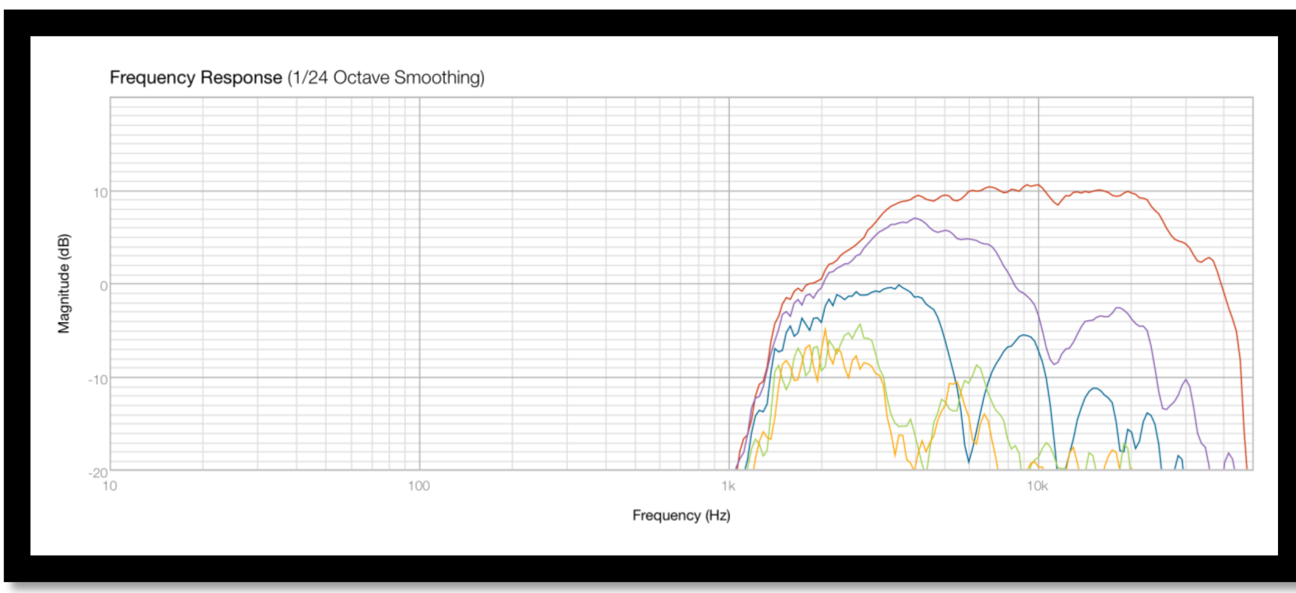
Vertical Off-Axis Response

Above Listening Axis



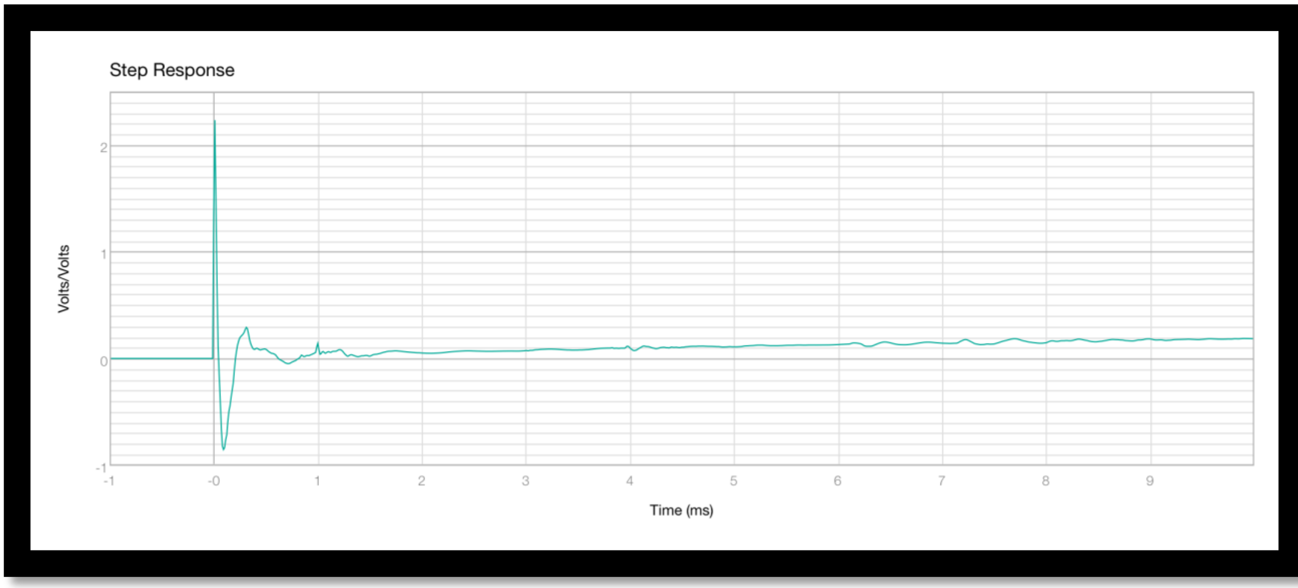
Frequency Response measured on axis (Red) & off axis at 15° (Purple), 30° (Blue), 45° (Green), and 60° (Orange) [measured at ½ meter at 89dB]

Below Listening Axis



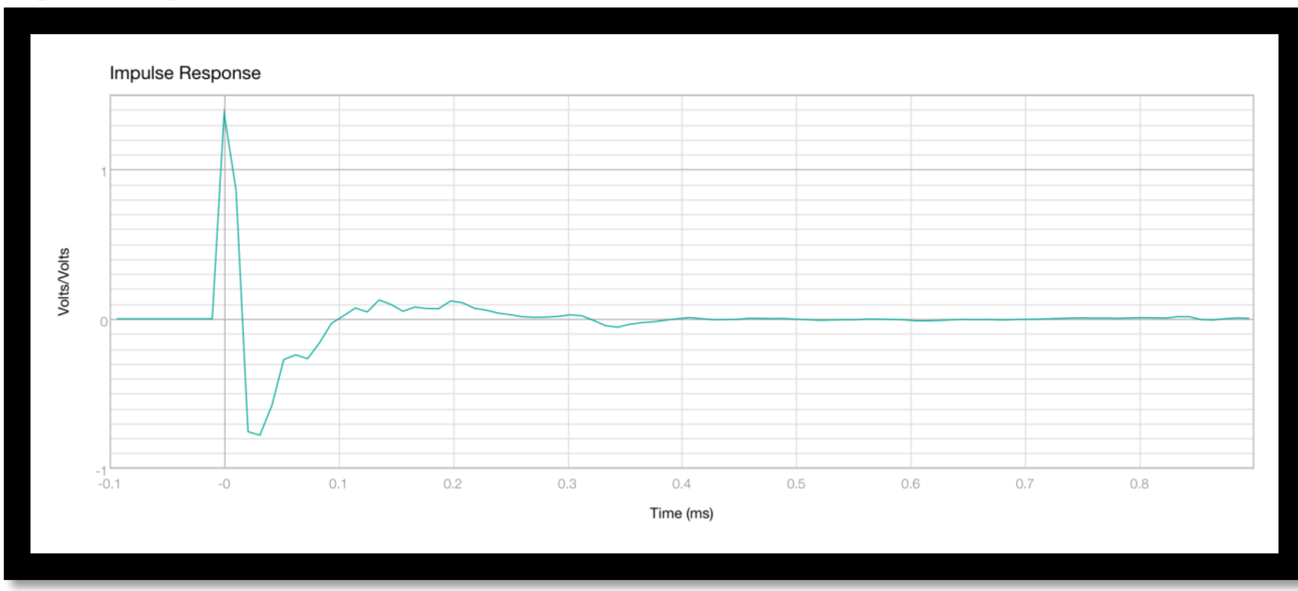
Frequency Response measured on axis (Red) & off axis at 15° (Purple), 30° (Blue), 45° (Green), and 60° (Orange) [measured at ½ meter at 89dB]

Step Response



Tweeter Step Response measured at ½ meter at 89dB

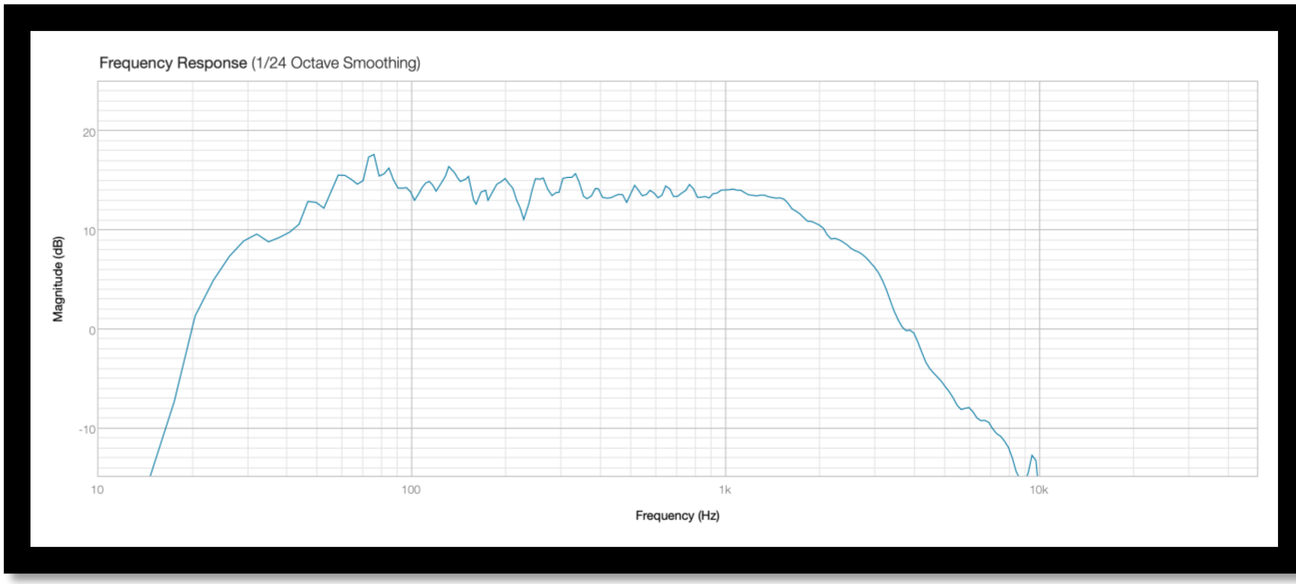
Impulse Response



Tweeter Impulse Response measured at ½ meter at 89dB

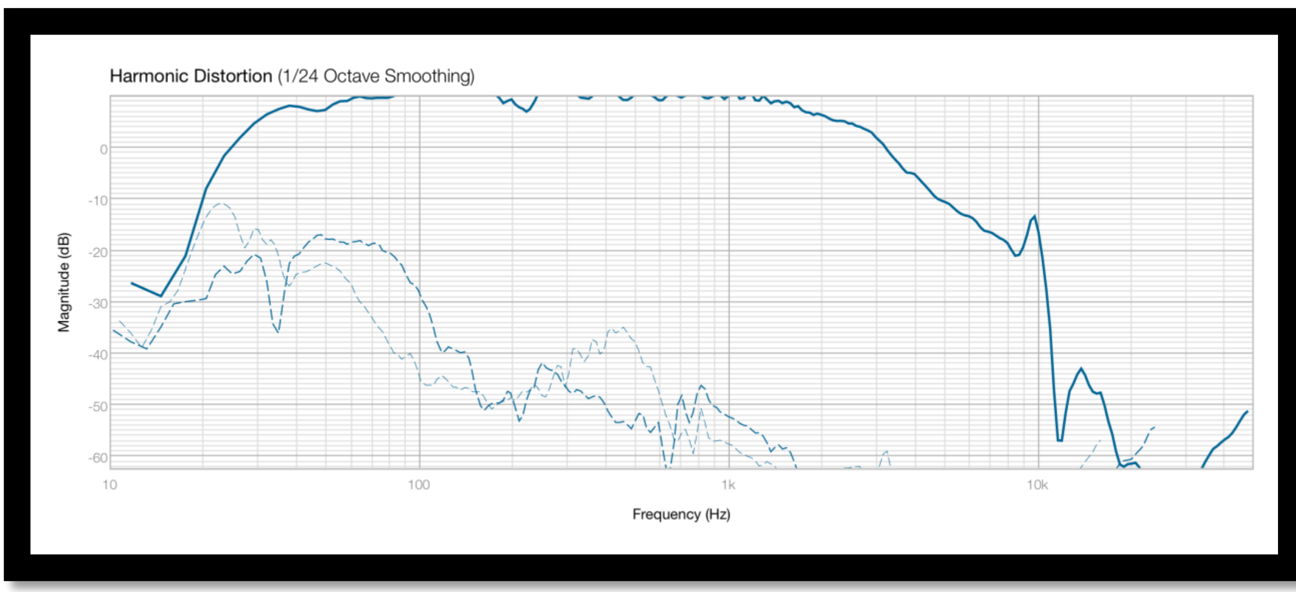
Driver Responses – Woofers

Frequency Response



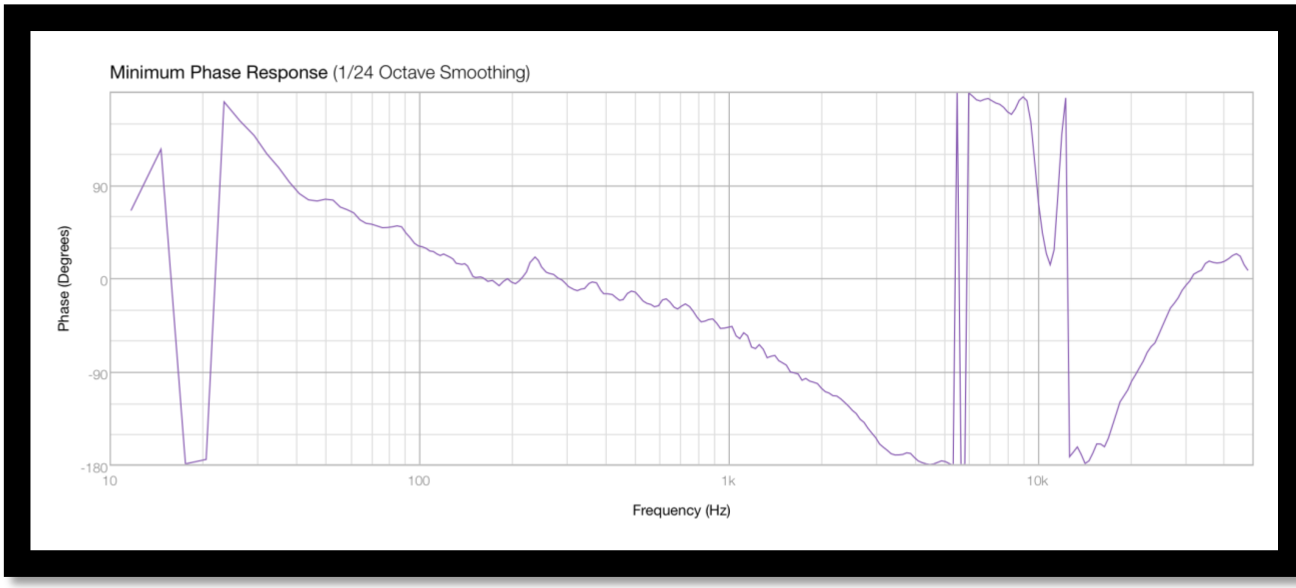
Woofers Frequency Response measured at ½ meter at 89dB

Harmonic Distortion



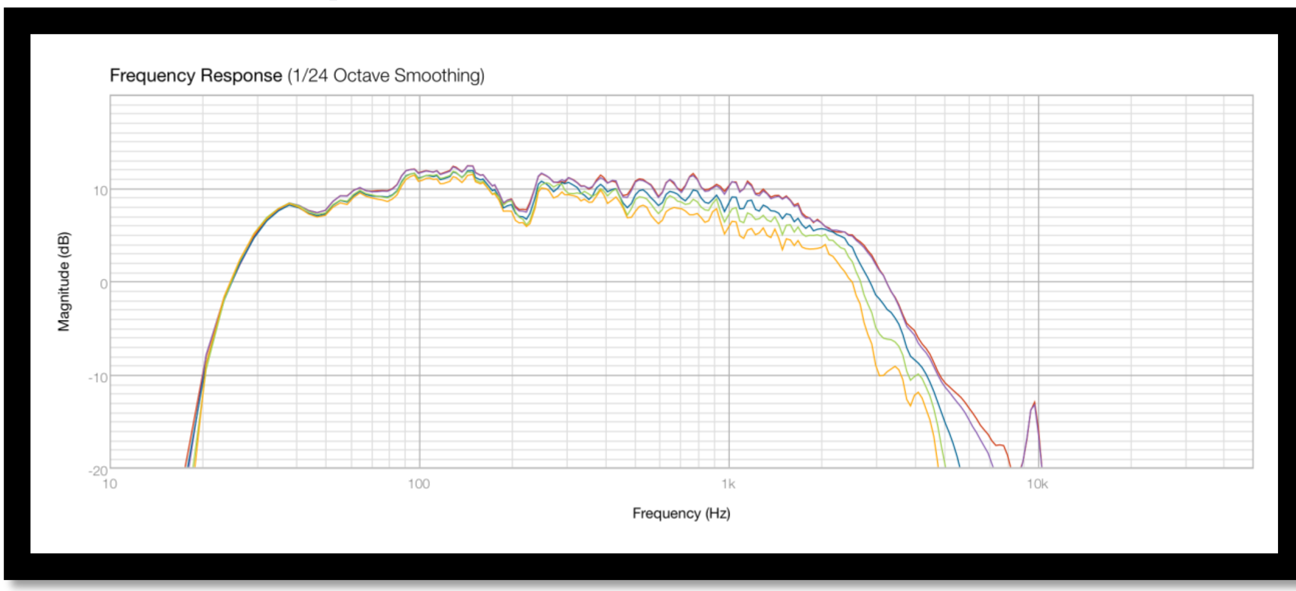
Woofers Harmonic Distortion measured at ½ meter at 89dB

Minimum Phase



Woofers Minimum Phase Response measured at ½ meter at 89dB

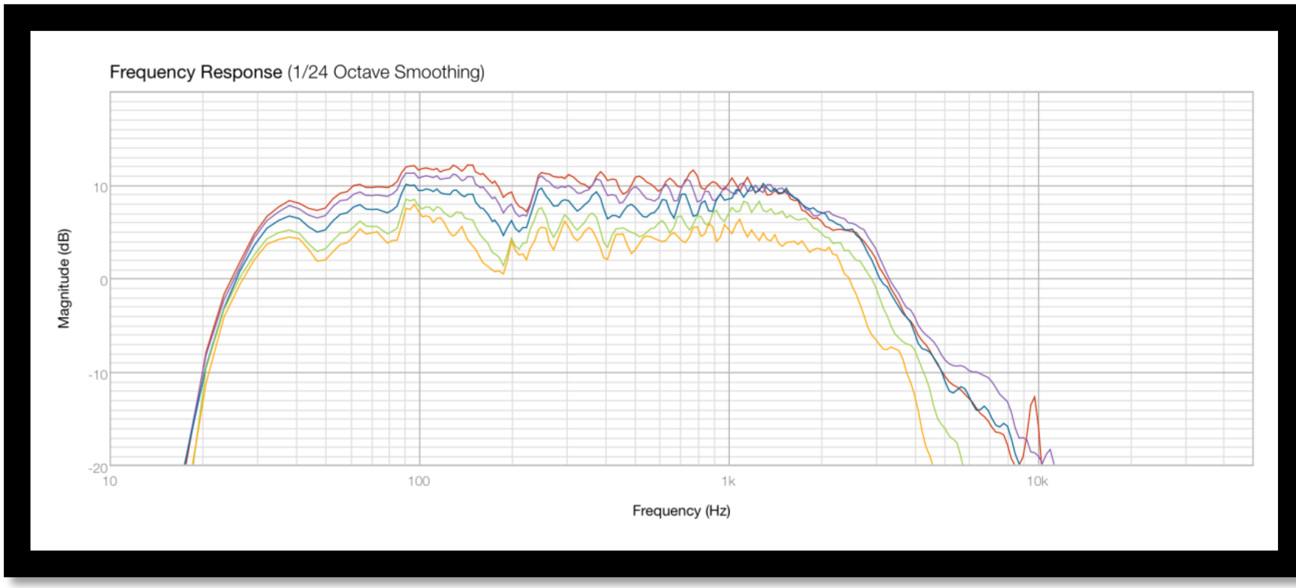
Horizontal Off-Axis Response



Frequency Response measured on axis (Red) & off axis at 15° (Purple), 30° (Blue), 45° (Green), and 60° (Orange) [measured at ½ meter at 89dB]

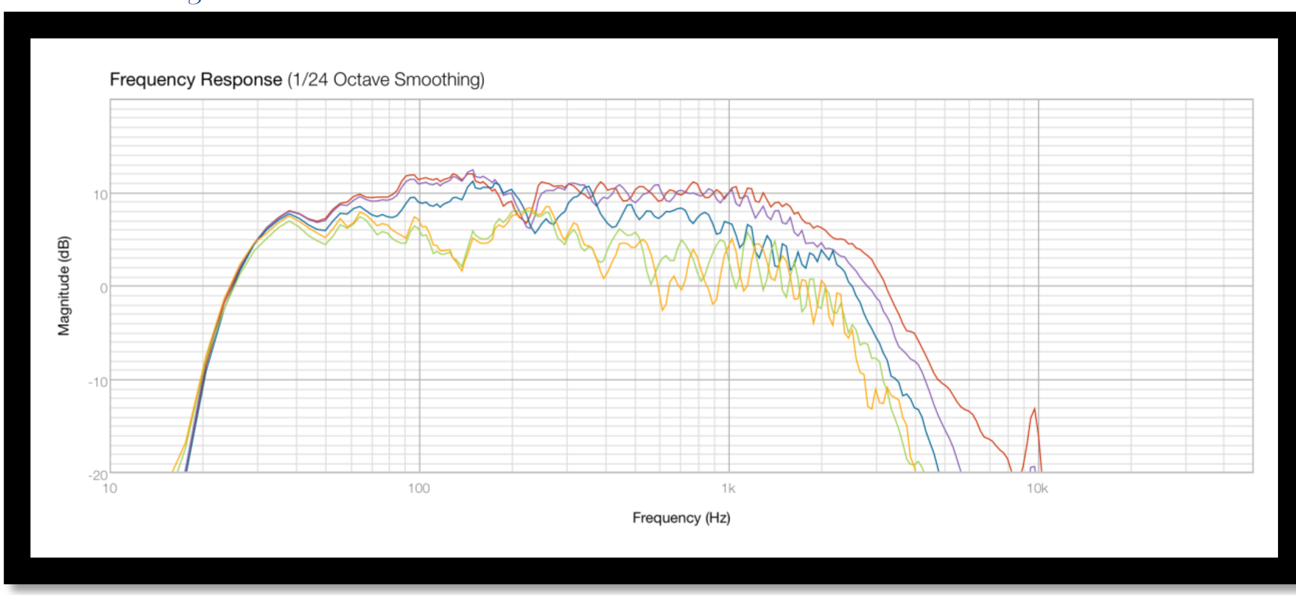
Vertical Off-Axis Response

Above Listening Axis



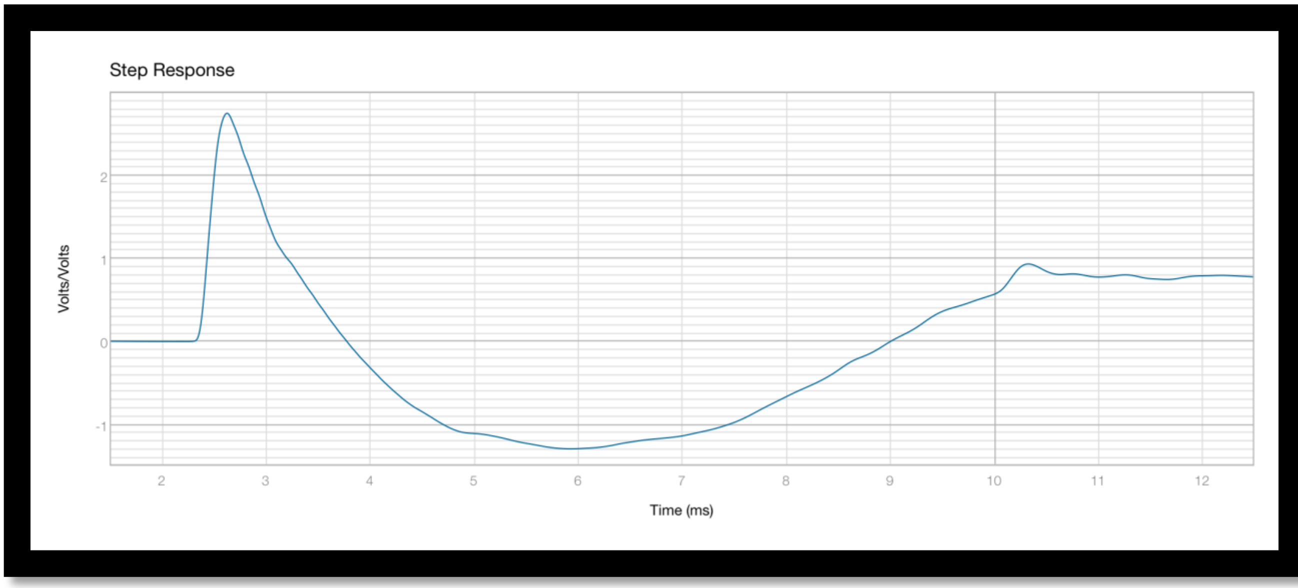
Frequency Response measured on axis (Red) & off axis at 15° (Purple), 30° (Blue), 45° (Green), and 60° (Orange) [measured at ½ meter at 89dB]

Below Listening Axis



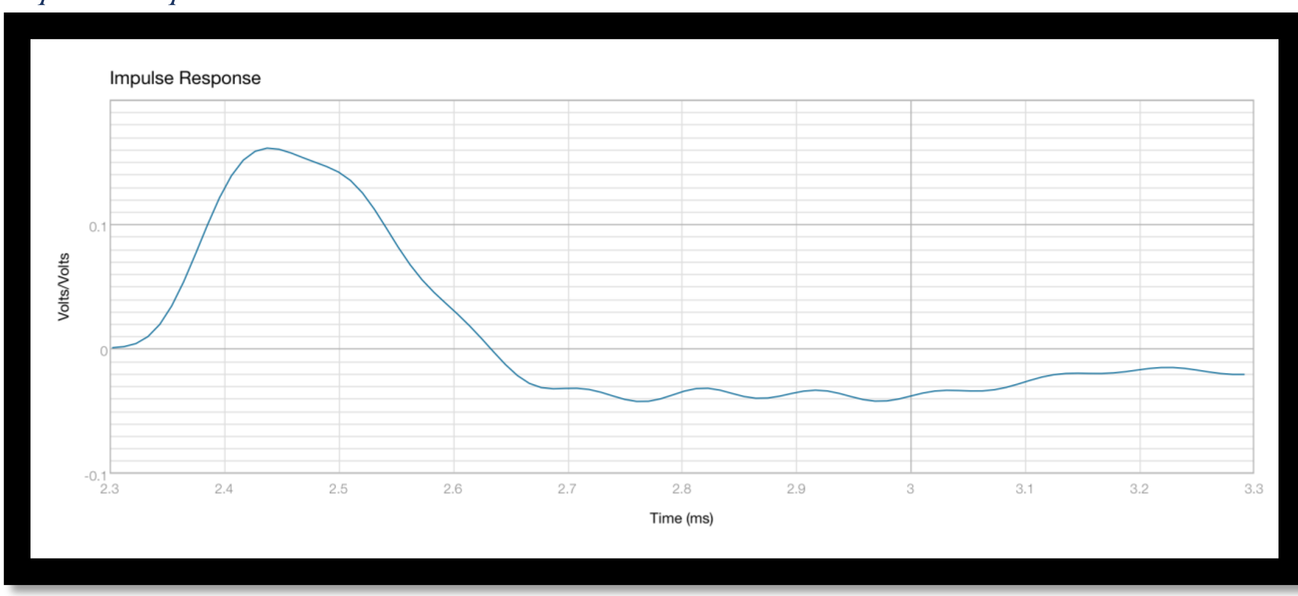
Frequency Response measured on axis (Red) & off axis at 15° (Purple), 30° (Blue), 45° (Green), and 60° (Orange) [measured at ½ meter at 89dB]

Step Response



Woofers Step Response measured at ½ meter at 89dB

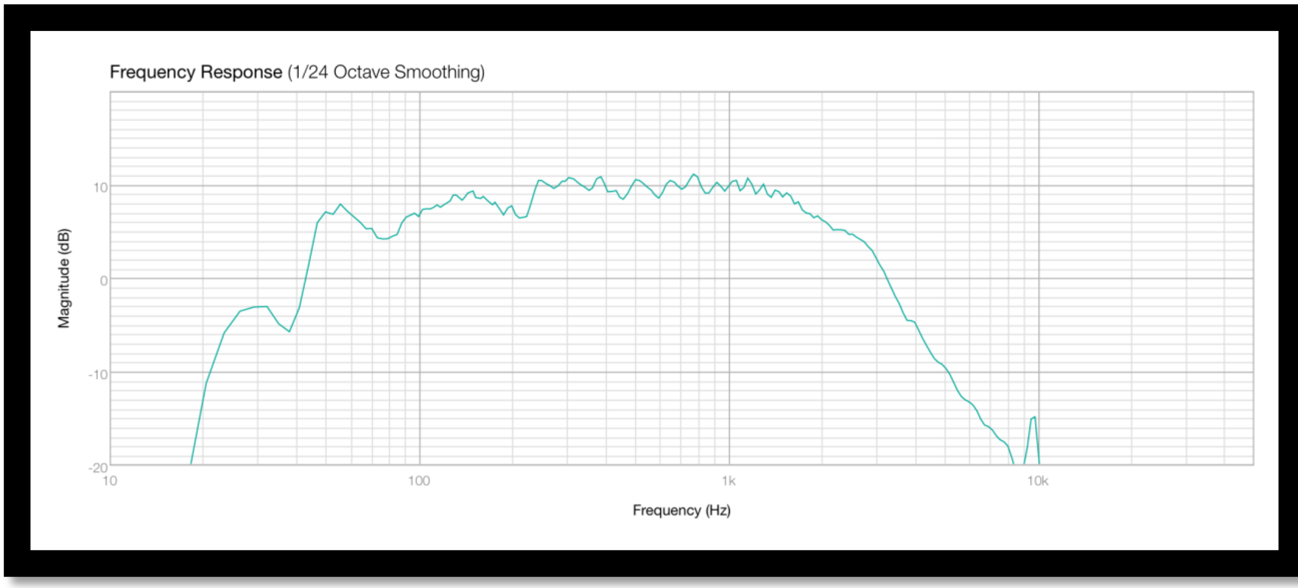
Impulse Response



Woofers Impulse Response measured at ½ meter at 89dB

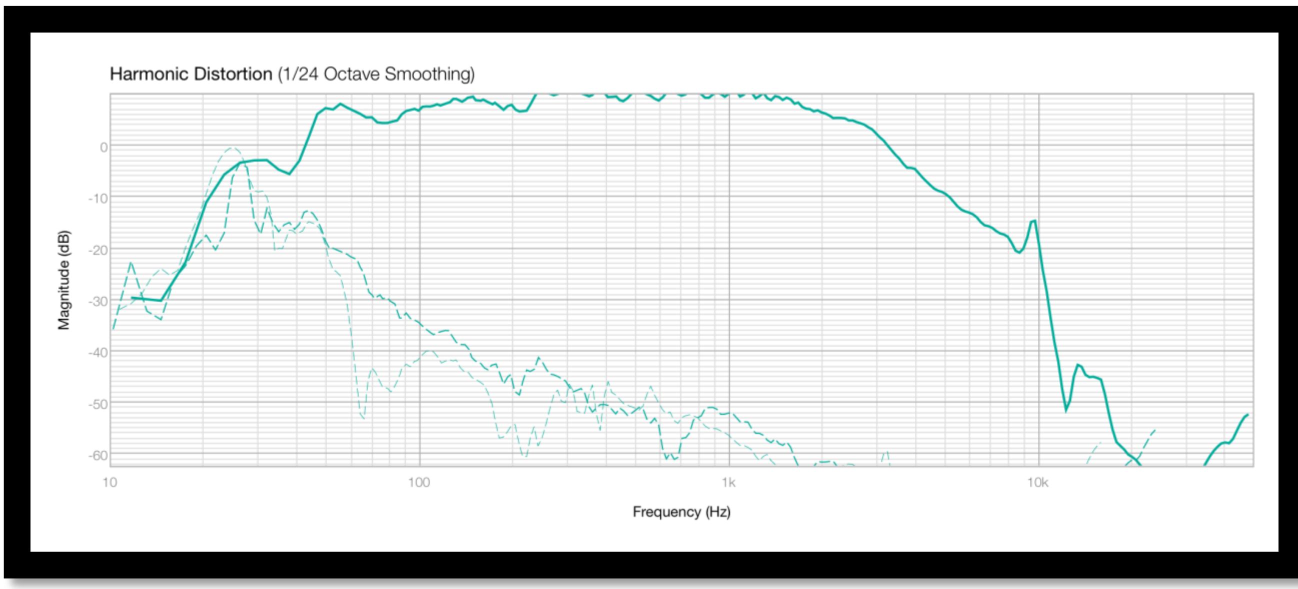
Driver Responses – Top Woofer

Frequency Response



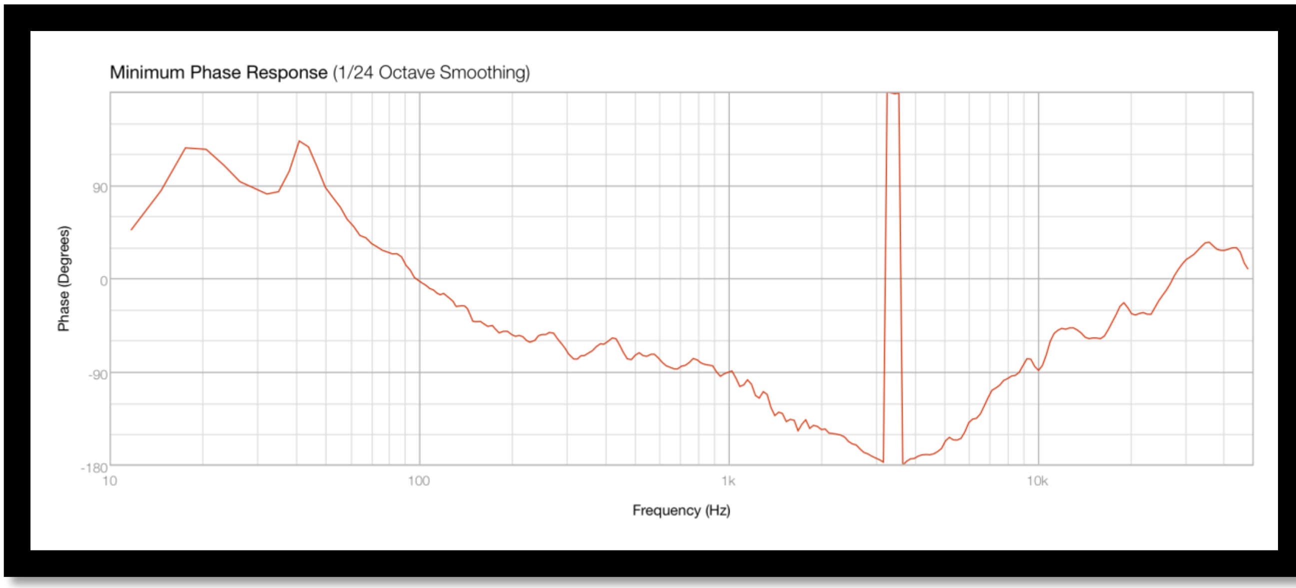
Top Woofer Frequency Response measured at ½ meter at 89dB

Harmonic Distortion



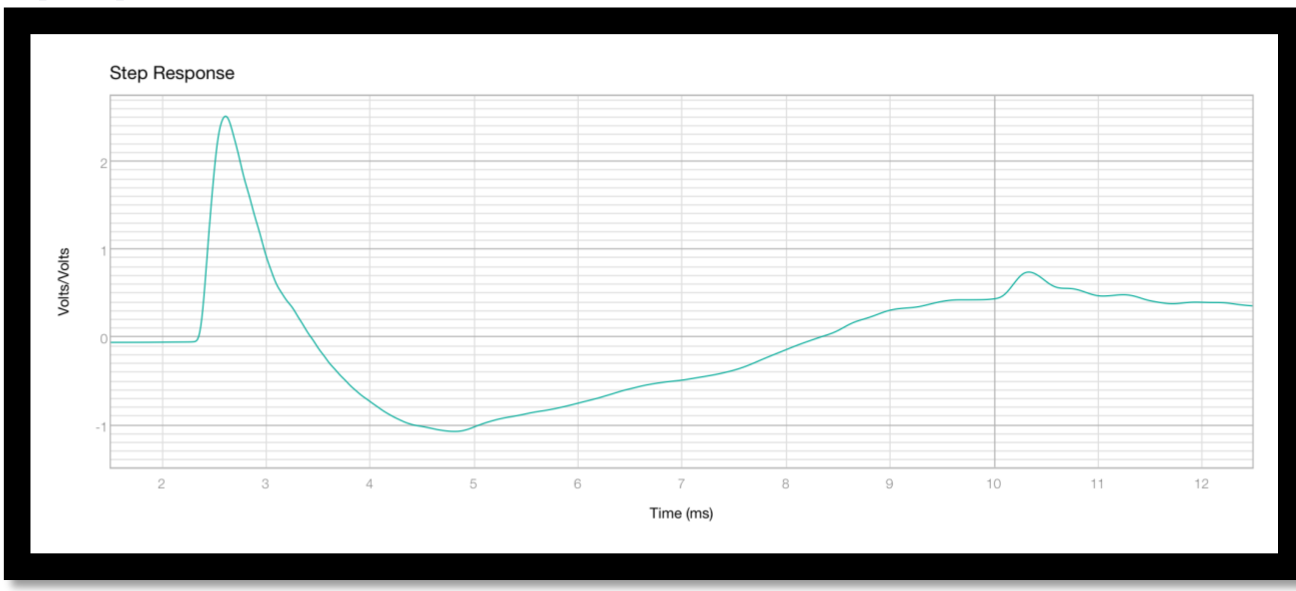
Top Woofer Harmonic Distortion Response measured at ½ meter at 89dB

Minimum Phase



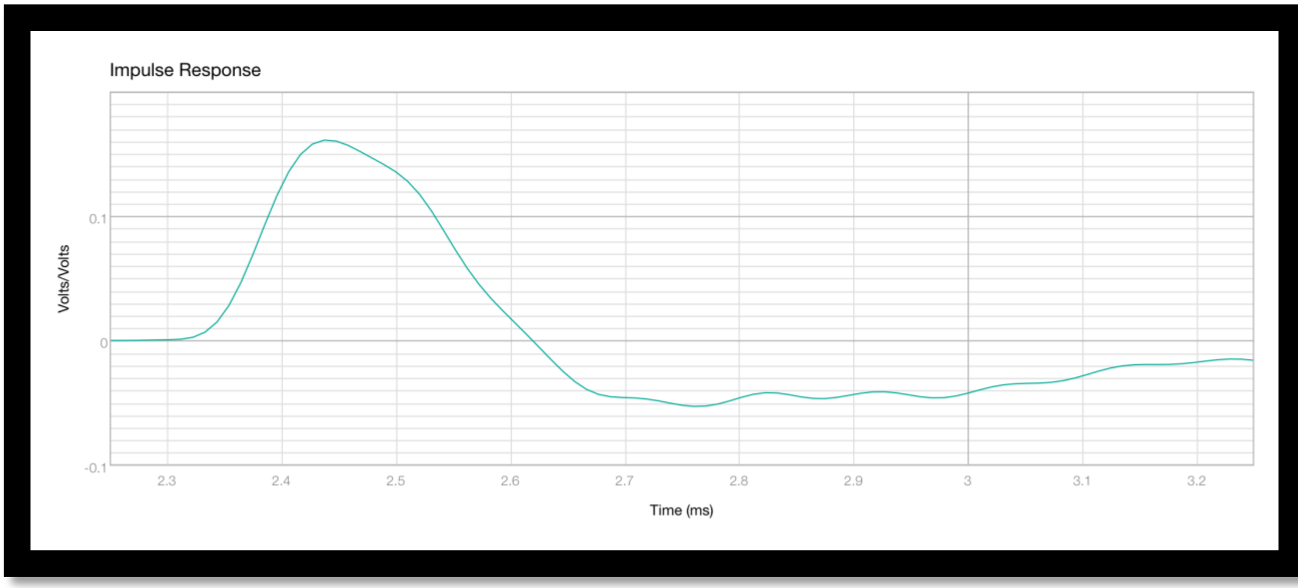
Top Woofer Minimum Phase Response measured at ½ meter at 89dB

Step Response



Top Woofer Step Response measured at ½ meter at 89dB

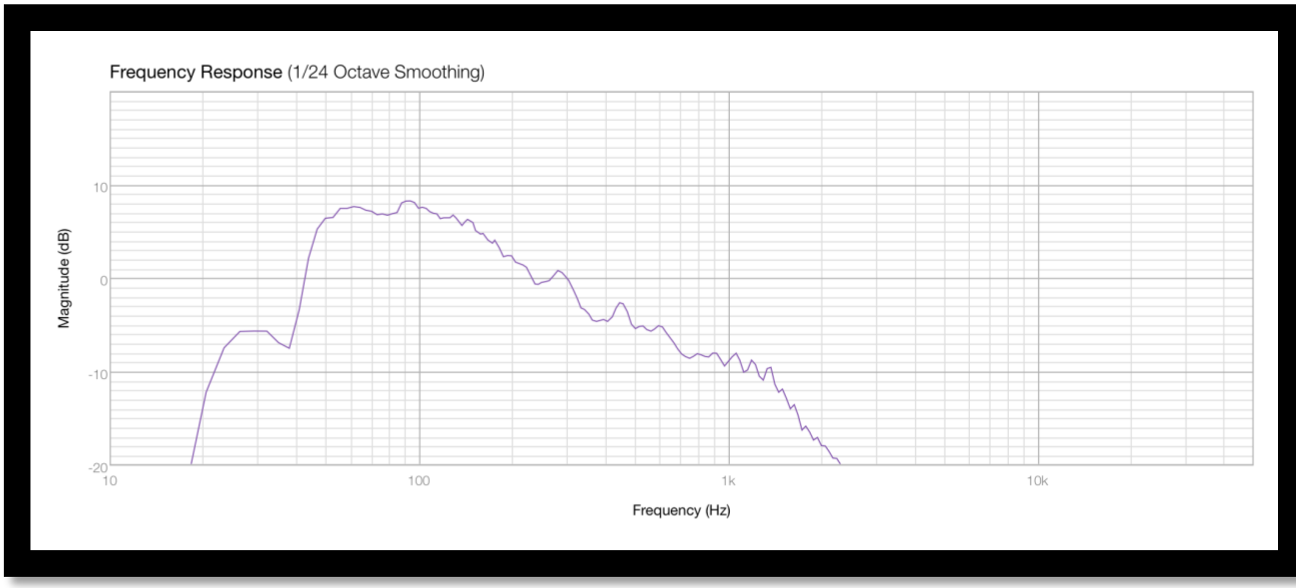
Impulse Response



Top Woofer Impulse Response measured at ½ meter at 89dB

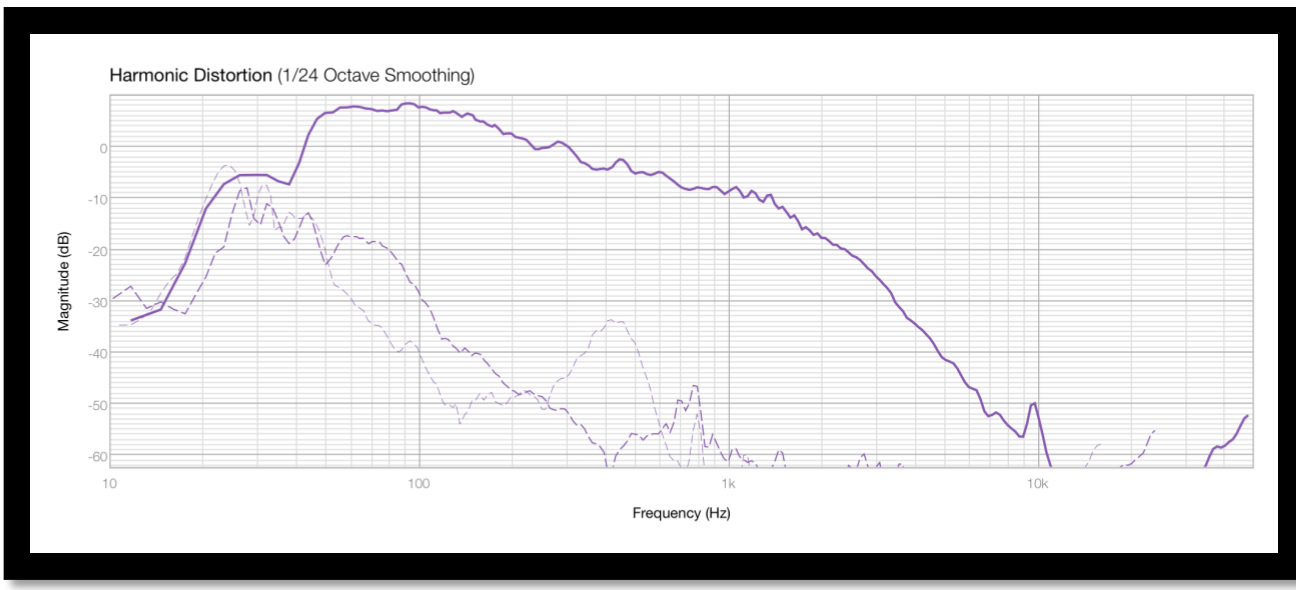
Driver Responses – Bottom Woofer

Frequency Response



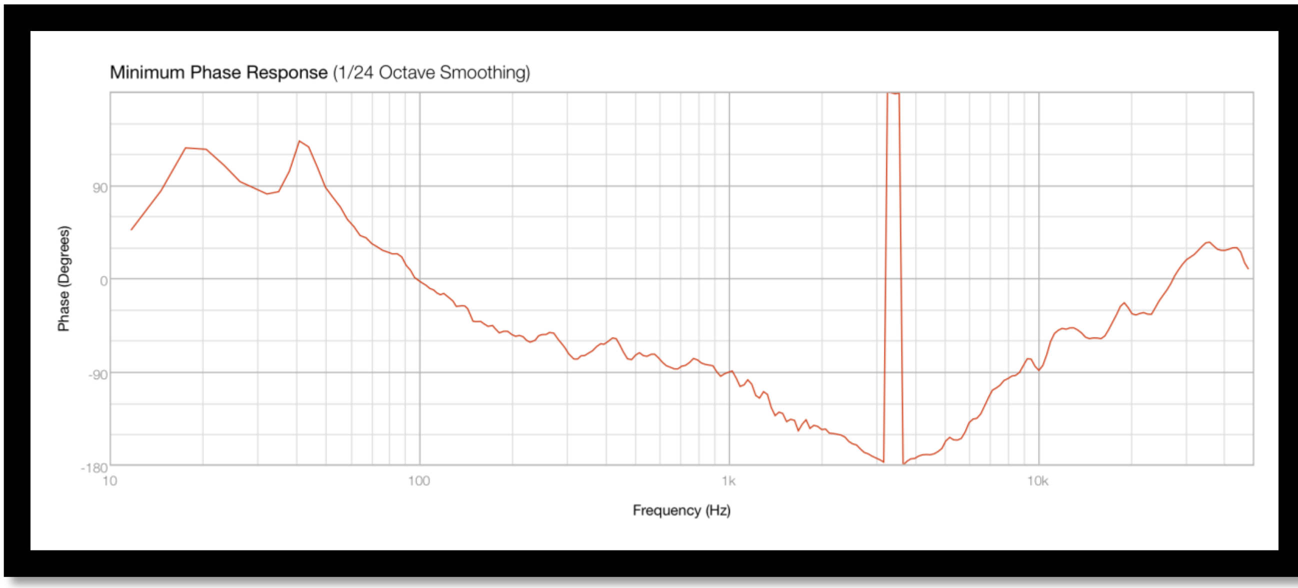
Bottom Woofer Frequency Response measured at ½ meter at 89dB

Harmonic Distortion



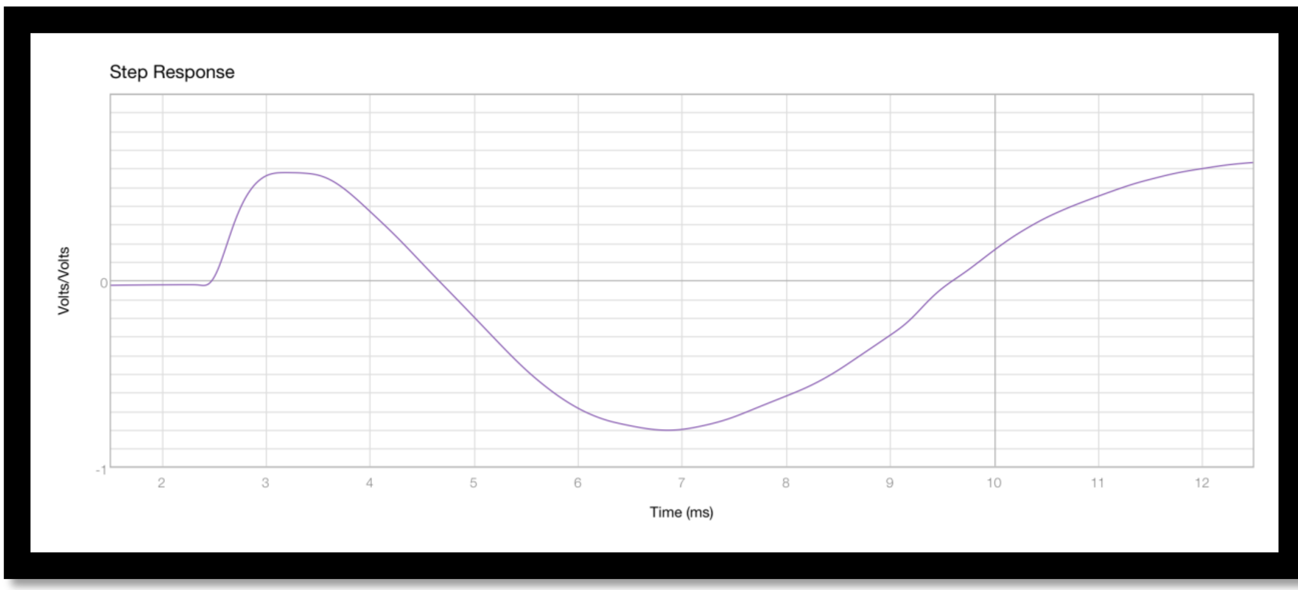
Bottom Woofer Harmonic Distortion Response measured at ½ meter at 89dB

Minimum Phase



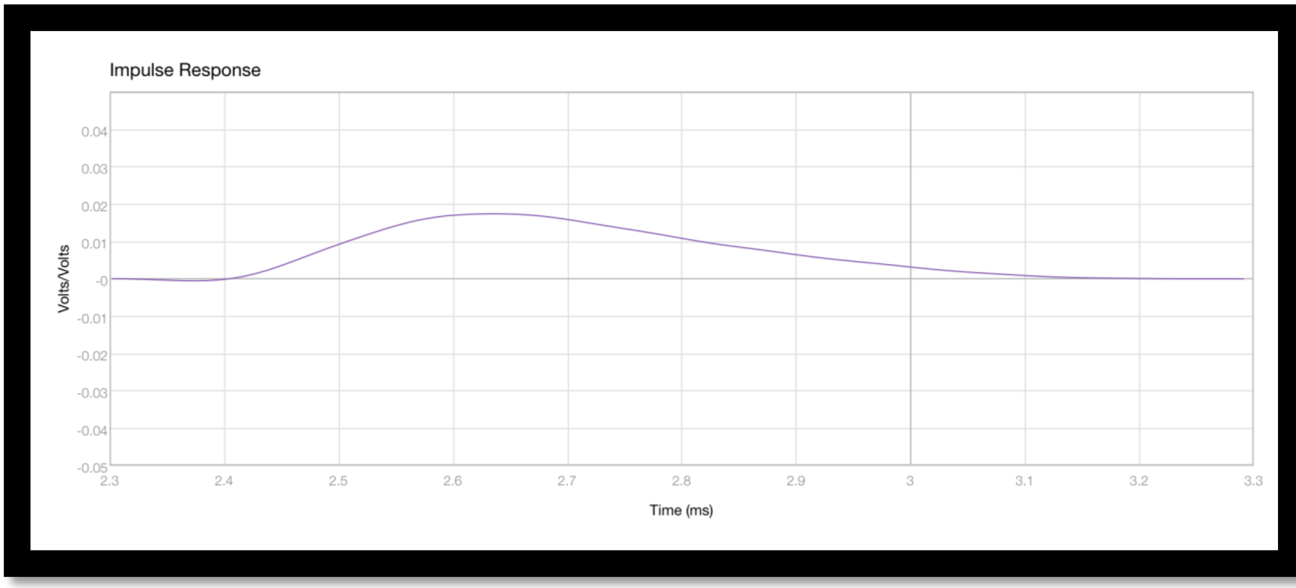
Bottom Woofer Minimum Phase Response measured at ½ meter at 89dB

Step Response



Bottom Woofer Step Response measured at ½ meter at 89dB

Impulse Response



Bottom Woofer Impulse Response measured at ½ meter at 89dB

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