Loudspeaker Enclosures

Physics 406 Spring 2016

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I: Introduction

As one who has spent many an hour listening to music at home, in the car, and at concerts, I have developed an interest in loudspeaker systems. Accordingly, I have been interested in improving my own home listening system. As it stands, my current setup, consisting of two bookshelf speakers and a subwoofer, yields adequate audio quality over most of the audible range, but I have noticed that the transition from the midrange to the sub-bass is somewhat disappointing. This problem has bothered me for some time, and I have been looking to add another set of speakers to bring that much needed component to my home listening experience. Fortunately, I came into possession of a pair of vintage, full-range Altec-755C 8-inch woofers, which likely have reasonable response in the bandwidth of interest, and I hope to integrate them into my sound system. However, the drivers are in need of enclosures, and as such, I have conducted my project this semester on loudspeaker enclosures, specifically the design, construction, and testing of an enclosure for one of the drivers I intend to add to my current sound system. In order to carry out my project, I wanted to know why an enclosure is so important in high-fidelity loudspeaker system, how to design an enclosure for a given loudspeaker, what characteristics to look for in the response of a high quality loudspeaker system, and most importantly, how to construct an enclosure that will meet my needs in terms of low to mid-range frequency response. I was also interested in what the effect of vents in a loudspeaker enclosure are as compared to a sealed enclosure, and when their use is appropriate.

II: Theory and Research

As I started out on my project, I had little idea of what the purpose of an enclosure really was, so I began my project with a little research into the theory of loudspeaker enclosures. I discovered that the primary purpose of a loudspeaker enclosure is to improve the low-frequency response. This fact was not too surprising, as I had done some experimentation driving my loudspeaker without an enclosure, and found that when simply sitting on the workbench without any sort of baffle, the low-frequency response seemed somewhat less than satisfactory. The cause of this sub-optimum response in free-air is interference. In general, a loudspeaker acts as an acoustic dipole, with acoustic waves being emitted from both sides of the speaker and those coming from the back being 180° out of phase from those coming from the front. The waves from the front of the loudspeaker are generally what we want to hear. The waves from the back, however, are for the most part unwanted noise, and can be rather problematic. At high frequencies, with short wavelengths, the rear waves are inconsequential; the wavelength will be too short for them to interfere with those in front to any significant degree. However, at lower frequencies and longer wavelengths, they will be able to 'reach around' the loudspeaker and interfere with the forward-directed waves. This result can be fairly well approximated as a high-pass filter, with a cutoff wavelength determined by the average distance the wave must travel to reach the other side of the speaker [1]. The obvious solution to this problem is a baffle, which increases the effective cutoff wavelength by increasing said distance, and thus lowers the cutoff frequency. In theory, we can extend the baffle to infinity, completely eliminating interference, but this is obviously not a practical solution; instead, we 'fold' that baffle back in on itself, sealing the back of the speaker off from the front creating a fairly good approximation to the infinite baffle.

While the primary function of an enclosure is to reduce/eliminate interference, there is more to it than that. In general, as with any acoustic source, the response of a loudspeaker is a function of the properties of the driver itself as well as the environment in which it is being operated (i.e. the atmospheric conditions/medium and the enclosure properties). A loudspeaker's response can be approximated well as a damped mass-spring system, with a stiffness/compliance associated with the driver's surround, a mass equal to the mass of the cone, and damping given by the driver's radiation resistance. The relevant variables which characterize the driver's performance, both electrically and mechanically, are the so-called Thiele/Small Parameters, which were introduced in a series of papers on loudspeaker enclosures published by Neville Thielle and Richard Small in the 80's [4]. As most of my modeling would be done in Bass Box Pro, I focused on those required for creating and modeling my enclosure designs in the software. These are:

f_s - Resonant frequency of the driver in free air

Q_{ms} - Mechanical Q or sharpness of mechanical resonance peak

Q_{es} - Electrical Q or sharpness of electrical resonance curve

Q_{ts} - Total Q, calculated from Q_{ms} and Q_{es}

V_{as} - Compliance of surround expressed in equivalent volume of air

X_{max} - Maximum displacement of diaphragm

Dia - Diameter of diaphraghm

R_e - DC resistance of voice coil

L_e - Inductance of voice coil

Z - Electrical impedance

P_e - Maximum electrical power

EBP - Efficiency Bandwidth Product, ratio of f_s and Q_{es}

I learned that it is best to measure these oneself, as a given driver's properties will change over time as it is broken in or material ages, and manufacturing tolerances in production can result in some variation of actual values as compared to the manufacturer's stated specifications. There are many different methods outlined for determining these variables through testing, but some, especially those associated with large signal response such as the excursion or power limit, can be risky to test, as one runs the risk of damaging the driver. I ultimately decided to test for what ones I could with the equipment available in the lab, and was fortunately able to find the rest online [5].

Once these parameters are known for a driver, we can look to the recommendations made by Thielle and Small in their papers regarding what type of enclosure a driver is best suited for, and what the additional variables associated with that enclosure should be, as well as model the response of the driver when placed in an enclosure. Fortunately, I had access to Bass Box Pro, which would do most of the modeling and design for me, so I did not research the mathematical techniques involved in modeling too thoroughly. The recommendations are summarized rather nicely in the text for Bass Box Pro [3]. For sealed enclosures, drivers with a low f_s, high V_{as}, large X_{max}, $EBP < 50$, and $Q_{ts} > 0.3$. Vented enclosures, on the other hand, are recommended for drivers with moderate f_s and X_{max}, $EBP > 100$, and Q_{ts} between 0.2 and 0.5.

Although we are relying on Bass Box Pro for most of our modeling concerns, we can consider qualitatively what the effect of a loudspeaker enclosure is beyond mitigating interference issues. As one might expect, mounting a driver in an enclosure brings a few more variables into the equation. Generally, enclosure types have an order associated with the number of energy storage methods. A sealed enclosure is 2nd order, and is characterized by its internal volume and the compliance of the air within, with energy being stored in the compression of the driver's surround/air in the enclosure and in the movement of the driver's cone. Vented enclosures are 4th order and are somewhat more complex, as there are the added variables associated with the resonance of the vents and the enclosure itself. In this case the additional methods for storage of acoustic energy are in the air in the vents, which acts approximately as an additional mass/spring system, coupled to the driver by the enclosed volume of air. Both types of enclosures, as mentioned earlier, also have the effect of baffling the driver, which adjusts the radiation resistance and eliminates the interference issue as discussed earlier.

Finally, it may be worth noting the ideal response and construction of a loudspeaker enclosure. For high-fidelity listening, the goal is to achieve as smooth a response as is possible in all aspects of the loudspeaker's acoustic properties. Obviously the primary aspect to be concerned with is the pressure amplitude, but it is also important to consider the phase response and group delay, which can result in poor audio quality if there are significant discontinuities or unusual resonances. Additionally, one should ensure that the velocity of the air in the vents is not too large to prevent unwanted noise or 'whistling'. In terms of construction, the ideal enclosure will be constructed out of dense material, to reduce losses due to vibration, and should be air-tight, to prevent losses due to leakage, both of which can have adverse effects of the efficiency of our system.

III: Procedure

In order to observe the effect these two types of enclosures will have on a loudspeaker, as well as design a proper enclosure for my loudspeaker, I began by determining the Thielle/Small parameters for my loudspeaker. As mentioned earlier, for the best results one should measure these as opposed to merely referring to the factory specifications, though for certain variables, the manufacturer's database values are the best one can get. In order to perform our measurements, we used the spectrum analyzer in the POM lab. The driver was placed in as open a space as was possible while still being close enough to connect to the spectrum analyzer, with it pointing away from any nearby walls or objects that might result in unwanted interference effects. The spectrum analyzer then relayed sinusoidal waveforms to the loudspeaker at low RMS voltages, and recorded the complex current and voltage across the voice coil, with measurements taken over a range of frequencies from about $2_{[Hz]}$ to $20_{[kHz]}$. This data was then processed using Matlab in order to obtain the electrical impedance of the loudspeaker in the frequency domain. This curve can be seen below in figure 1. Examining the results, we can see that the impedance has a resonance at $f_s = 66.23_{[Hz]}$ with a magnitude of $18.9_{[\Omega]}$, which corresponds to the resonant frequency of the loudspeaker in free-air. We can also find the impedance of the loudspeaker, which is defined to be the magnitude of the first minima after resonance, which occurs at $229.63_{[Hz]}$ with a magnitude of $7.23_{[\Omega]}$. Furthermore, we can calculateQ_{ms}, Q_{es}, and Q_{ts} from the curve by defining a ½ power point, $Z_0 = \sqrt{R_e \times Z_{max}}$, using the impedance magnitude at resonance, Z_{max} and the DC resistance R_e. We then find $f_{low/hi}$, the frequencies at which the impedance attains the value Z_0 above and below resonance. We then calculate

$$Q_{ms} = \frac{f_s}{f_{hi} - f_{low}} \sqrt{\frac{Z_{max}}{R_e}} \cong 2.442 \tag{1}$$

$$Q_{es} = \frac{Q_{ms}}{\frac{Z_{max}}{R_e} - 1} \cong 1.395 \tag{2}$$

$$Q_{ts} = \frac{Q_{ms} Q_{ts}}{Q_{ms} + Q_{ts}} \cong 0.8876 \tag{3}$$

$$EBP = \frac{f_s}{Q_{es}} \cong 47.48 \tag{4}$$

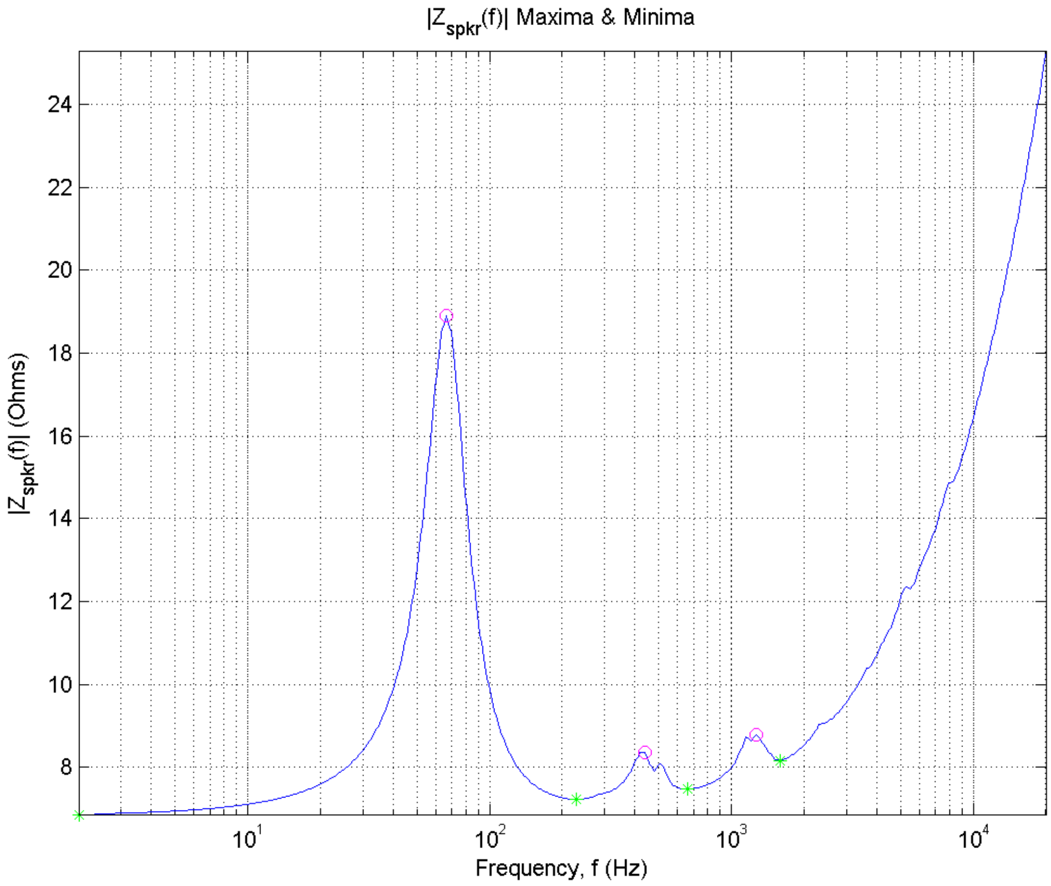


Figure 1. Electrical Impedance Magnitude of AL 755-C [Ohm] in free-air vs. Frequency [Hz].

We also measured the inductance of the voice-coil at $1_{[kHz]}$ (industry standard) to be $300_{[\mu H]}$, as well as the various physical dimensions of the driver. We were unfortunately unable to measure the remaining Thielle-Small parameters as we did not have a test enclosure, and did not want to risk damaging the driver.

Values for these parameters were found online [5]. Whether or not these values are accurate is debatable, as the properties of a driver will change over time and with use, but, with no other options, they are better than nothing. The values for the measured and researched parameters are summarized in the table below:

f_s $[Hz]$	Q_{ms}	Q_{es}	V_{as} $[L]$	X_{max} $[mm]$	Dia	R_e $[\Omega]$	L_e $[\mu H]$	Z $[\Omega]$	P_e $[Watts]$	EBP	Q_{ts}
66.23	2.442	1.395	42.68	0.3	16	7.2	0.3	7.23	15	47.48	0.8876

With the values, it is possible to look back to the recommendations for choosing an enclosure type as summarized in Bass Box Pro. We can see that the calculated Q_{ts} and EBP are both seemingly well suited to a sealed enclosure. However, it also appears that our X_{max}, which is unusually small, may be better suited to a vented enclosure, and that our f_s may be a bit higher than would be optimal for our purposes, as the resonance in the enclosure will be higher than in free-air. Whatever the case, I decided to design two identical enclosures, one sealed and one vented, in order to perform a listening test as well as observe the effect the added orders of the vented enclosure would have on the response of a loudspeaker.

At this point, we entered all of the relevant variables into Bass Box Pro, and set about designing our enclosures. Sealed enclosures are generally grouped into two types, the acoustic suspension and the infinite baffle. The infinite baffle type has an internal volume greater than the V_{as} of the driver, meaning that the stiffness of the surround will the dominant variable in determining the response. The acoustic suspension, on the other hand, will have a volume less than the V_{as}, and the stiffness of the enclosed volume of air will be the dominant spring, which is generally far more linear than that of the surround. In making our test design, however, we used Bass Box Pro's suggestion function, which suggests an internal volume based on the given parameters and the desired performance, which yielded an enclosure with a volume approximately twice the V_{as} of the driver (about three cubic feet). The vented enclosure was designed in a similar manner, having the same dimensions, but with the addition of two 2-inch diameter vents, giving the enclosure an f_b of $34.48_{[Hz]}$. Generally one would choose a specific alignment or tuning for a desired Q_{tc} or total system Q, but since we had access to Bass Box Pro, and were primarily interested in observing the effects of the vent, we did not need to go to the trouble. The details of the two designs and the resulting model can be seen in the appendix (pages 13-18). The ratio of the dimensions of the enclosure are approximately in accordance with the golden ratio in order to reduce unwanted resonances in the enclosure. Because the designs are nearly identical, we needed only construct the vented type enclosure, as sealing the vents off will effectively transform the vented enclosure into the sealed enclosure.

With the designs prepared, I set about constructing the enclosure over spring break. The material used for construction was medium density fiberboard, which has a relatively high density and is quite rigid, which should help to reduce losses through the vibration of the walls of the enclosure. A few adjustments to the dimensions of the enclosure were made for ease of construction, such as the change from a single 3-inch diameter vent to two 2-inch diameter vents. These minor alterations are reflected in the designs in the appendix and ultimately had a negligible effect on the predicted response. The vents were constructed using PVC pipe and were mounted on the rear of the enclosure in order to help reduce unwanted mid-range frequency noise, and since they will primarily emit sound in the low-frequency limit, the location and orientation are not as crucial as long as they are within about a quarter wavelength in the low-frequency limit (to prevent significant interference effects). The enclosure is mainly held together with glue, and during the gluing process, I was sure make the enclosure as air-tight as possible to prevent leakage losses. The back of the enclosure is held on with removable screws, and is sealed using weather stripping. Ideally the box would be filled with some type of acoustic insulation, but this may have interfered with the vents, so the box was left unfilled. The driver was front mounted about one inch to the left of the center to further mitigate unwanted resonances and was made air-tight with some more weather stripping. To plug the vents, I purchased a pair of test plugs for 2-inch diameter PVC piping (which turned out to be more trouble than they were worth). No crossover was used, as the speakers will ultimately have their own amplifiers which will be used to adjust levels/cutoff frequencies. Unfortunately, I failed to thoroughly document the construction process, but the designs can be found in the appendix.

With the enclosure constructed and the driver properly mounted, I brought the enclosure into the lab for some testing. Ultimately, two different types of tests on the enclosure with the vents open/sealed were performed. We first measured the electrical properties in the same way as was done for the driver in free-air in order to observe the effect the enclosure on resonance and impedance. We then measured the pressure and particle velocity on axis at $1_{[m]}$ from the cone of the driver over a range of frequencies from $2_{[Hz]}$ to $20_{[kHz]}$ to observe the difference between the sealed and vented enclosures. The resulting data was then processed in Matlab, and the results are shown in the graphs below.

IV: Test Results and Performance Evaluation

To begin, let us discuss the electrical measurements of the two different loudspeaker systems. In terms of overall shape of the impedance curve, we can see that the sealed enclosure's impedance is nearly identical to that of the free-air test. The analysis in Matlab revealed that the maximum magnitude of the impedance was $17.58_{[\Omega]}$ and appeared at $66.23_{[Hz]}$. This result was somewhat surprising, as we expected the sealed enclosure's resonance to occur at a higher frequency than the free-air resonance (the model predicting a resonance of $15.13_{[\Omega]}$ at a frequency of $80.06_{[Hz]}$, which can be seen in figure 3), but the test results are almost identical to those obtained in the free-air test. There are a few possibilities for why we obtained this strange result. For the free-air test, we had the loudspeaker leaning up against some acoustic insulation in order to direct the acoustic waves away from the nearest walls. This foam may have acted in a manner similar to that of an enclosure, and thus increased the resonant frequency of our free-air test. This, combined with the fact that the compliance of the air in our sealed enclosure is more than double that of the surround, may be the cause of this peculiar result. We can also calculate the Q_{tc} of the entire system using the same method we used to calculate Q_{ts} for the driver in free-air, obtaining the value 1.094, which is notably higher than the value predicted by Bass Box Pro, 0.888.

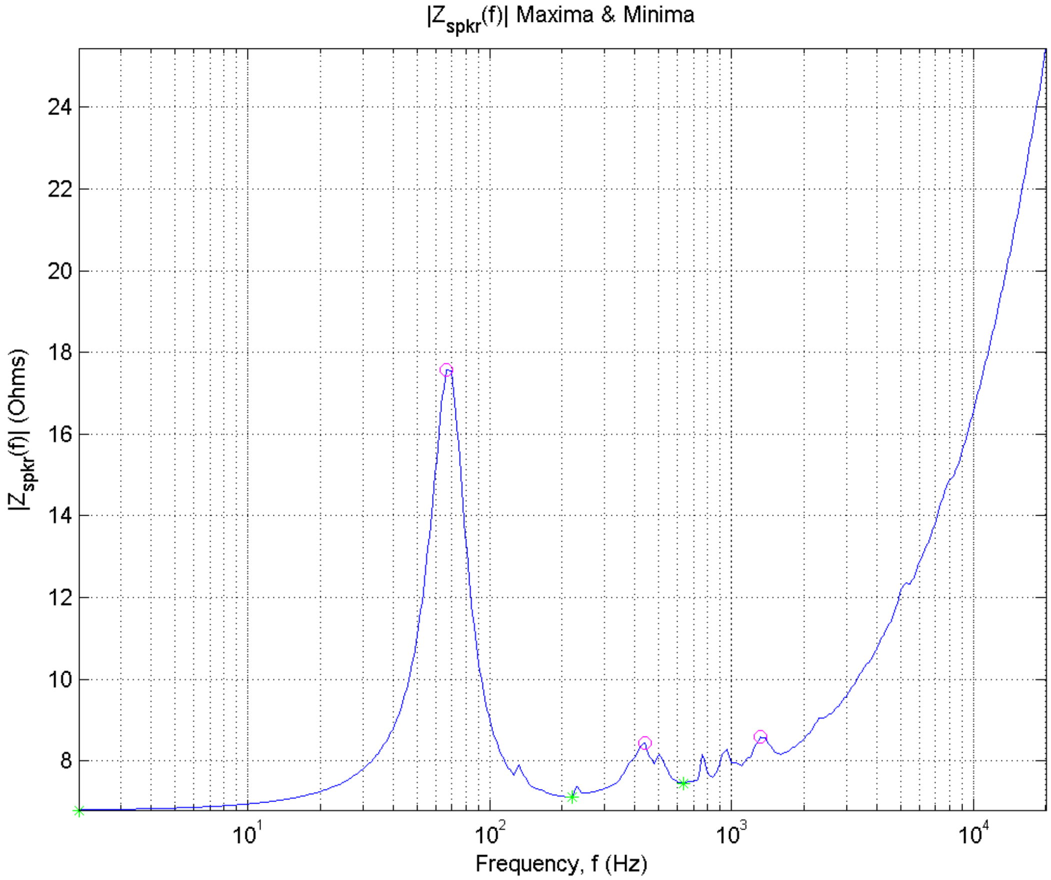


Figure 2: Electrical Impedance magnitude of driver in sealed enclosure $[\Omega]$ vs frequency $[Hz]$

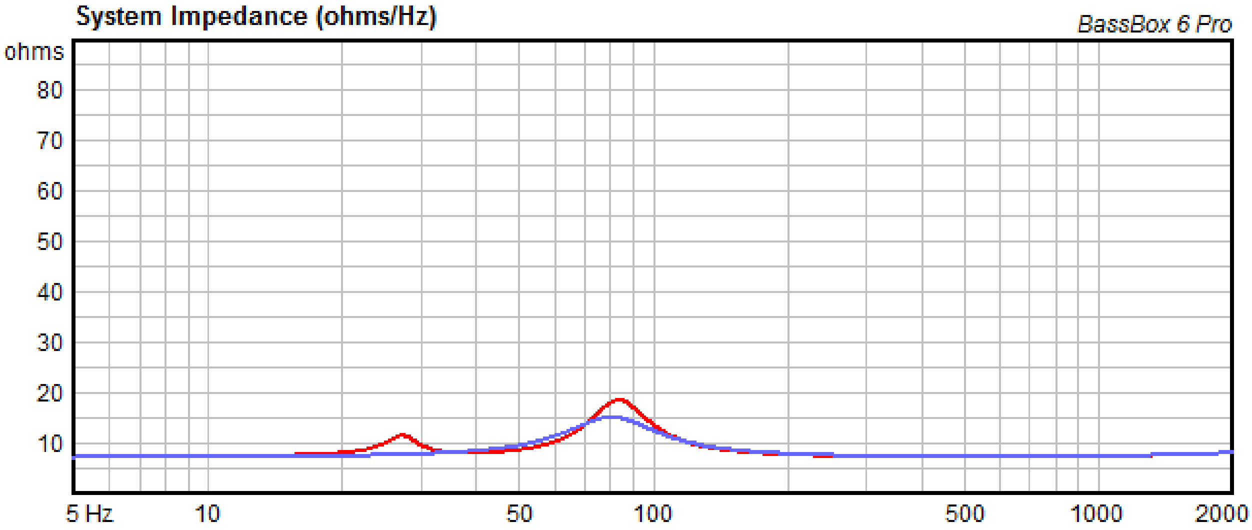


Figure 3: Bass Box Pro model of electrical impedance magnitude $[\Omega]$ vs frequency $[Hz]$

The results for the vented enclosure were somewhat more similar to what was expected, although the somewhat inaccurate measurement of the resonant frequency is still evident. As can be seen on the graph below, the impedance of the vented enclosure is a little bit more complicated. In addition to the resonance of the driver in the enclosure (appearing at $72.62_{[Hz]}$ with a magnitude of $17.24_{[\Omega]}$), we can see the resonance of the vents (appearing at $28.91_{[Hz]}$with a magnitude of $11.02_{[\Omega]}$). The resonance of the enclosure itself corresponds to the minimum between the two peaks, with a frequency of $34.76_{[Hz]}$. The discrepancy in the driver resonance, which was predicted to appear at $83.26_{[Hz]}$, is consistent with our hypothesis that the free-air measurement was in fact higher than the actual resonant frequency of our driver, and the fact that the predicted vent resonance and enclosure resonance are nearly the same as was predicted in Bass Box Pro (with frequencies of $34.48_{[Hz]}$ and $27.03_{[Hz]}$ for the enclosure and vents respectively) seems to confirm our suspicions. The calculated Q_{tc} of this system using the driver resonance came out to 1.29, which is significantly higher than the value obtained for the sealed enclosure, and is illustrative of the somewhat less smooth response obtained from the vented enclosure and notably more complex phase response that is characteristic of vented enclosures.

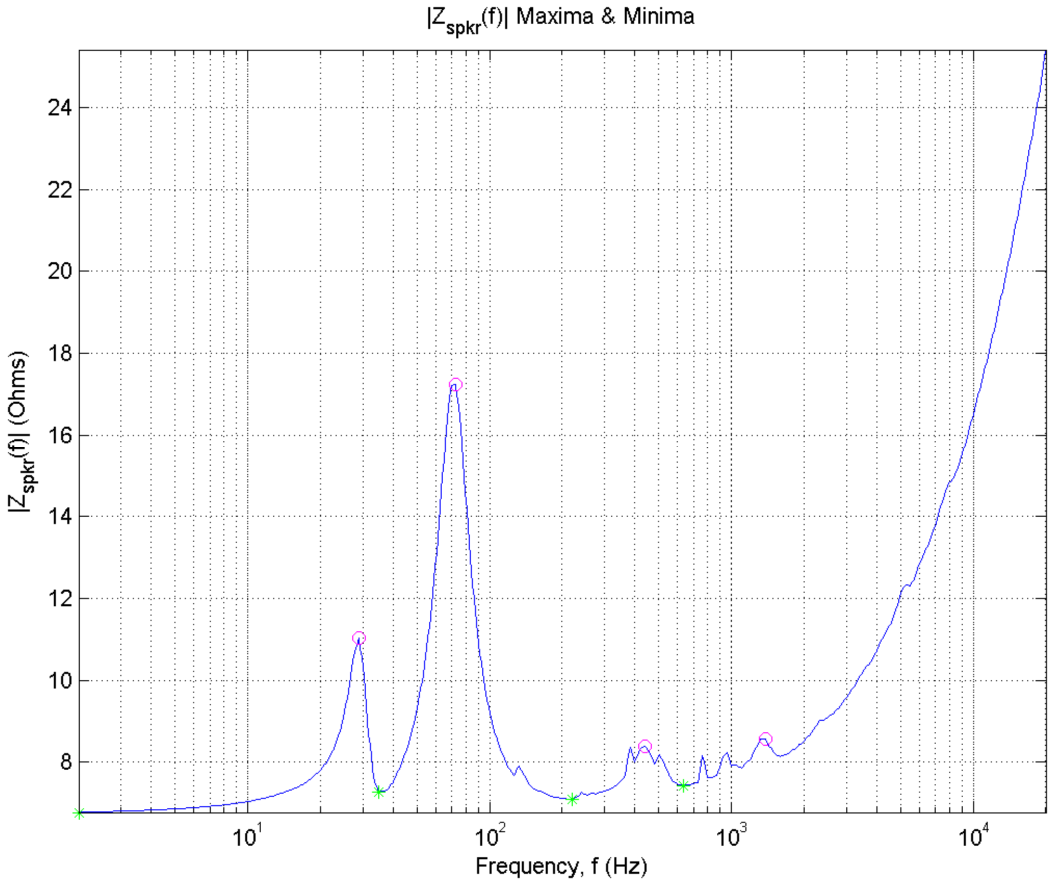


Figure 4: Electrical impedance magnitude of driver in vented enclosure $[\Omega]$ vs frequency $[Hz]$

The acoustic measurements on the two different enclosures were taken in order to observe the effect that adding vents to an enclosure would have on the various acoustic aspects of the system, and is generally the more important of the two tests, as the acoustic pressure is ultimately what the listener will hear. The data was somewhat noisy due to the room acoustics and background noise in the lab, so the results of each test on their own is not particularly useful. However, when comparing the two response curves, we can observe some notable differences between the two types of enclosures. The most notable difference between the two is the difference in SPL in the low frequency limit. At very low frequency ($< 20_{[Hz]}$) there is not much of interest, as this is well below the operating range of this system, and the data is cluttered by low frequency background noise from the duct work in the lab. However, above $20_{[Hz]}$, we begin to see some appreciable response from the system. Here we observe that the SPL of the vented enclosure is notably higher than the sealed enclosure. Between $20_{[Hz]}$ and $30_{[Hz]}$ we see the red line is significantly higher than the blue, corresponding to the resonance of the vents in our enclosure. Because the vents are oriented away from the P-U mic, the amplitude is still rather low, but still considerably higher than the sealed enclosure. Continuing along the curve, we can note the sharp peak around $35_{[Hz]}$. This is believed to correspond to the resonance of the enclosure itself, though it may be an artifact due to the room acoustics, as our model does not predict such a high amplitude at this frequency. Above this point, we observe that the two curves begin to approach one another, but with the red curve still slightly above the blue up to about $200_{[Hz]}$, though what appear to be standing waves resultant from the room's acoustics make it difficult to discern the total difference in SPL. This is, for the most part, in agreement with the predictions made in Bass Box Pro.

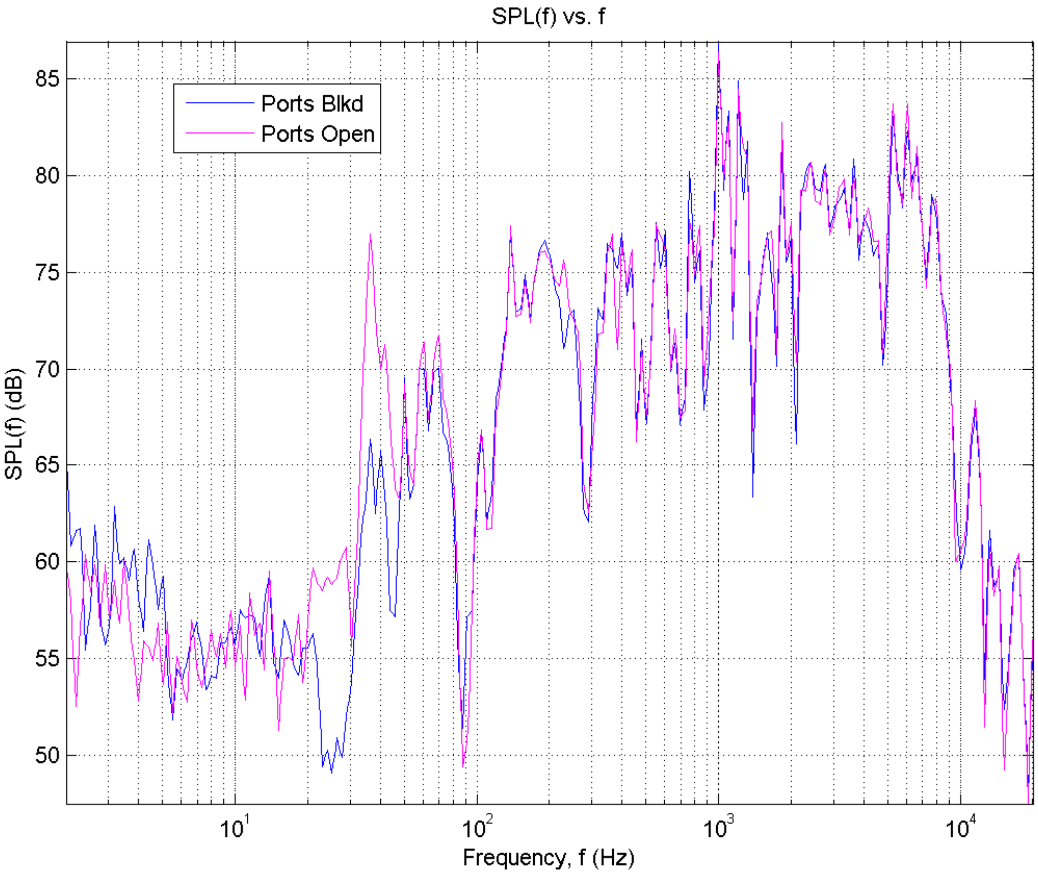


Figure 5: Sound Pressure Level $[dB]$ vs Frequency $[Hz]$ of sealed (blue line) and vented (red line) enclosures

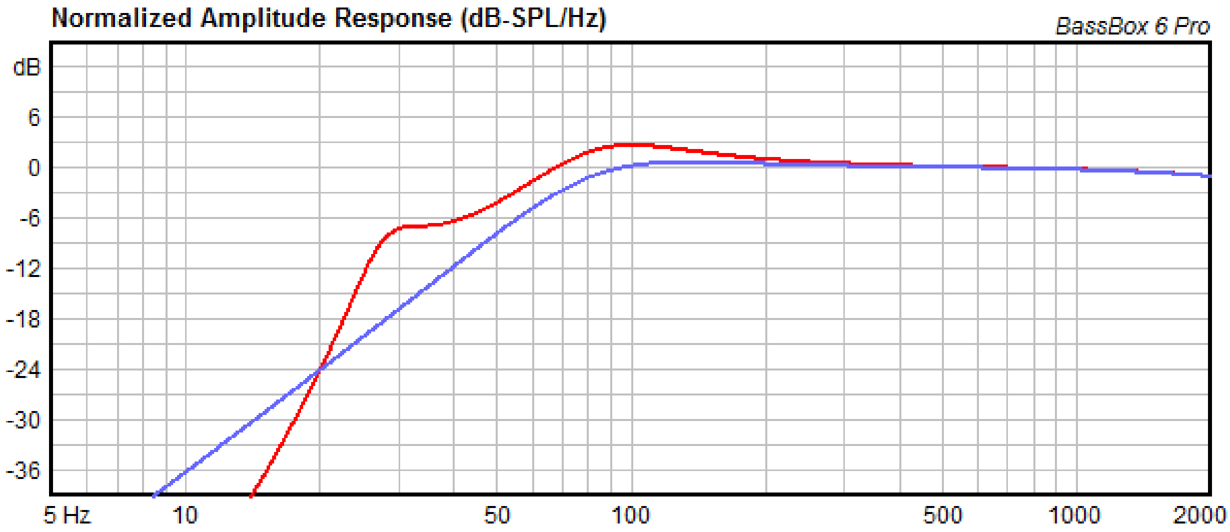


Figure 6: Bass Box Pro model of amplitude response $[dB]$ vs frequency $[Hz]$

Ultimately, these measurements tell us that venting our enclosure results in a more complex impedance, adding a second resonance corresponding to the vents which we can interpret to cause a more complex, less smooth phase response, as predicted in our model in the appendix (page 15). Furthermore, the vents result in an increase in the amplitude response of the system near the resonant frequency of the driver. However, this improved low frequency performance comes at the cost of flat pressure amplitude, phase response, and group delay. This issue could be addressed to some degree with the use of an external equalizer, but this would not be particularly helpful in dealing with the issues in the group delay or phase, which appear to be the largest issues with this particular system as can be seen in the appendix. It seems that the sealed enclosure is the best option for hi-fidelity listening.

V: Conclusion

To summarize our findings, we learned that an enclosure's primary purpose is to eliminate interference between the waves emitted from the front and back of the loudspeaker. However, the enclosure can further improve the response by helping to help smooth out the response of the loudspeaker, as well as potentially improve efficiency in a manner similar to that of a Helmholtz resonator. If the driver has the appropriate characteristics, it is possible to improve the range of a driver's response with the use of a vented enclosure, which extends the low frequency response by exciting the resonances associated with the vents and the enclosure itself, which can be tuned to achieve different acoustic responses, though there will generally be some loss in fidelity due to the increased complexity of the impedance of the system and difference in phase between the vents and the driver, especially if the driver's parameters do not fall within the recommended ranges. We learned how to choose an enclosure for a loudspeaker by measuring the Thielle/Small parameters, and by building and testing an enclosure for our driver, we confirmed the effect of vents in an enclosure and familiarized ourselves with proper enclosure construction techniques. Finally, we were able to infer from our tests that the sealed enclosure is likely the best option for our driver, for its lower Q value, less complex phase response, and smooth amplitude response. Moving forward, I intend to construct a set of enclosures using what I have learned and to incorporate the two into my home listening sound system.

References:

Loudspeaker design texts:

[1] Murphy, John L. *Introduction to Loudspeaker Design*. Escondido, CA: True Audio, 1998.

[2] Dickason, Vance. *The Loudspeaker Design Cookbook*. Peterborough, NH: Audio Amateur, 1995.

[3] DE Harris. *Bass Box 6 Pro User Manual*. 5th ed. N.p.: CreateSpace Independent Platform, 2013

Collection of Neville Thielle and Richard Small's JAES papers:

[4] Read, Richard. "Articles." *Read Research*. N.p., 2016. Web. 20 Jan. 2016. - http://www.readresearch.co.uk/articles.php

Thielle/Small parameters for Altec Lansing 755-C:

[5] Petion, Dominique. "Paramtres De THIELE Et SMALL Du ALTEC 755C, Sans Filtre Ni Ampli." *Paramtres Haut-parleur De THIELE Et SMALL, Sans Filtre Ni Ampli*. N.p., 14 Nov. 2011. Web. 20 Jan. 2016 - http://petoindominique.fr/php/mysql_thiele_seul_ref.php?ref=755C

Guide used for calculating driver Q values:

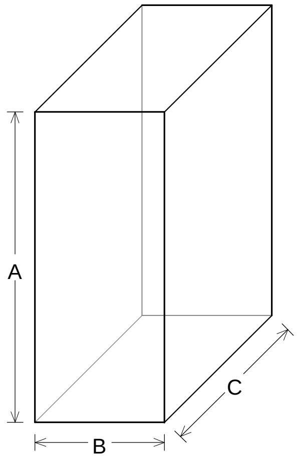
[6] http://www.wavecor.com/Measuring_driver_Q-values.pdf

Custom Vented Box Design

By Physics 406, University of Illinois at Urbana-Champaign

Box Properties

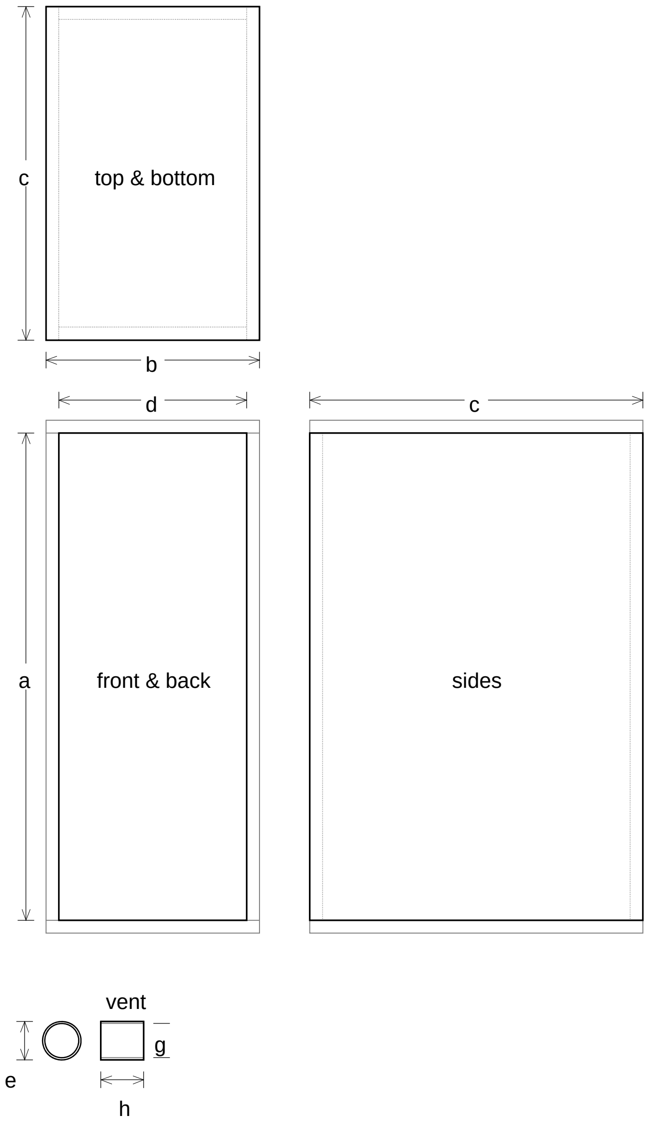
--*Description*-Name: sealed vents
Type: Vented Box
Shape: Prism, square
--*Box Parameters*-Vb = 3.158 cu.ft
V(total) = 3.266 cu.ft
Fb = 34.48 Hz
QL = 5.301
F3 = 53.81 Hz
Fill = none
--*Vents*-No. of Vents = 2
Vent shape = round
Vent ends = one flush
Dv = 2 in
Lv = 2.5 in



Driver Properties

Fs = 66.23 Hz
Qms = 2.442
Vas = 42.68 liters
Xmax = 0.3 mm
P-Dia = 16 cm
Qes = 1.395
Re = 7.2 ohms
Le = 0.3 mH
Z = 7.23 ohms
Pe = 15 watts

--*Description*--
Name: 755 c
Type: Standard one-way driver
--*Configuration*-**No. of Drivers = 1**
--*Driver Parameters*--
--*External Dimensions*--
A = 30 in
B = 12.5 inC = 19.5 in
--*Internal Dimensions*--
A = 28.5 in
B = 11 in
C = 18 in
--*Wall Thickness*--
Front = 0.75 in
Side = 0.75 in



Box Parts

Box Shape: Square Prism

1 Top, 1 Bottom: depth (c) = 19.5 in width (b) = 12.5, thickness = 0.75 in 1 Front, 1 Back: height (a) = 28.5 in width (d) = 11, thickness = 0.75 in 2 Sides: height (a) = 28.5 in depth (c) = 19.5, thickness = 0.75 in

--*Driver Mounting*- Mounting: Front

--*Vent Parts*--

2 Ducts: outside diameter (e) = 2.25 in inside diameter (g) = 2 in length (h) = 2.5 in

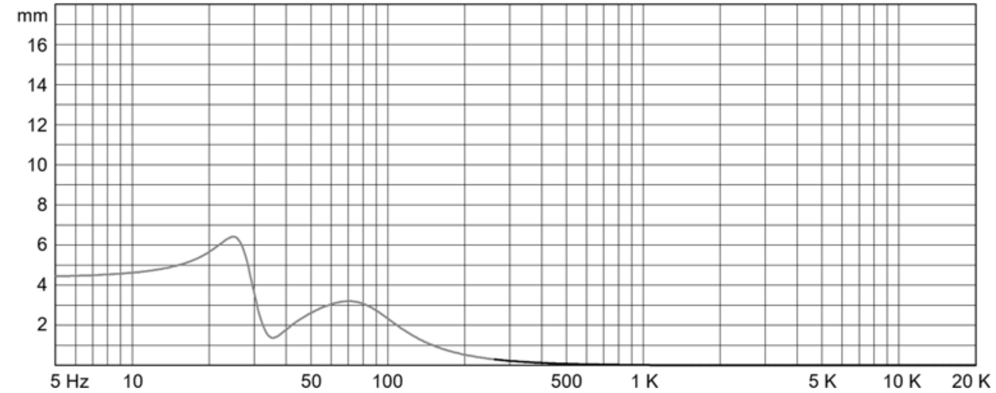
--*Misc Objects Inside or Part of Box*--

Object: object 1

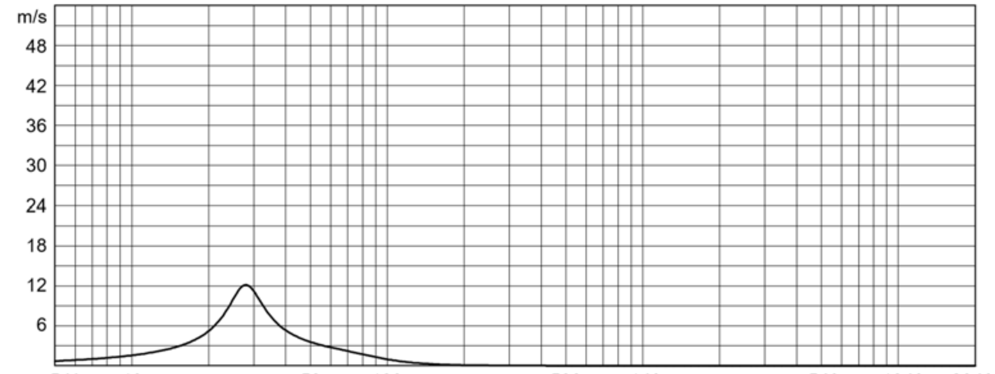
No. of Objects: 1

Volume: 0.0951 cu.ft (reduces box) Shape: Known Volume (any shape)

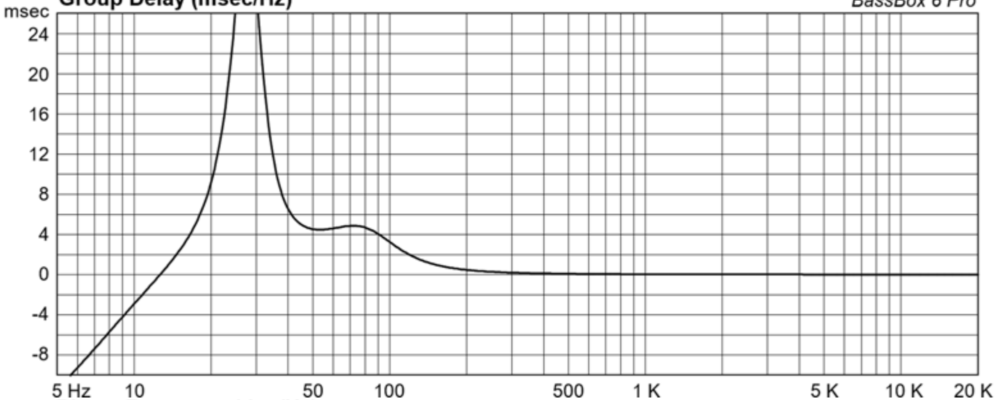
Cone Displacement (mm/Hz) with 15 watts



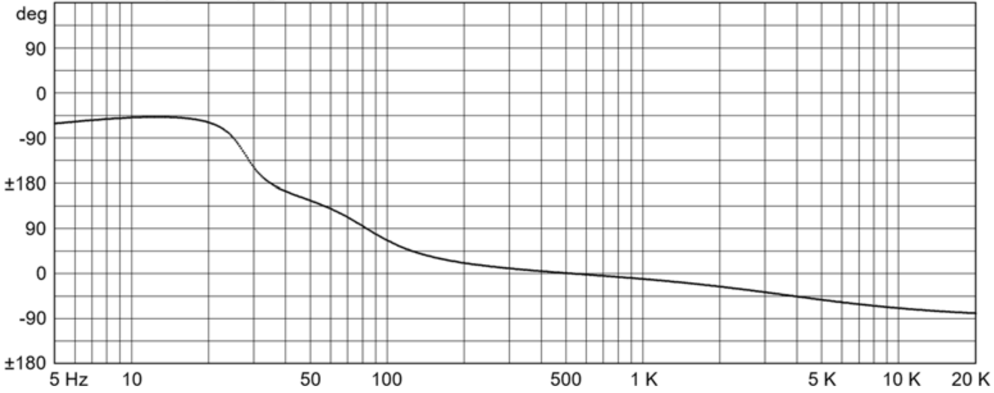
Vent Air Velocity (m/sec/Hz) with 15 watts



Group Delay (msec/Hz)



Phase Response (deg/Hz)

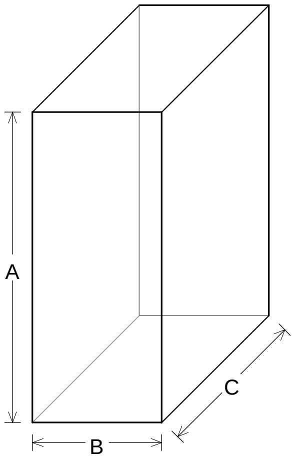


Custom Closed Box Design

By Physics 406, University of Illinois at Urbana-Champaign

Box Properties

--*Description*-Name: proposed vent Type: Closed Box
Shape: Prism, square
--*Box Parameters*-Vb = 3.164 cu.ft
V(total) = 3.266 cu.ft
Qtc = 0.888
QL = 5.301
F3 = 67.43 Hz Fill = none

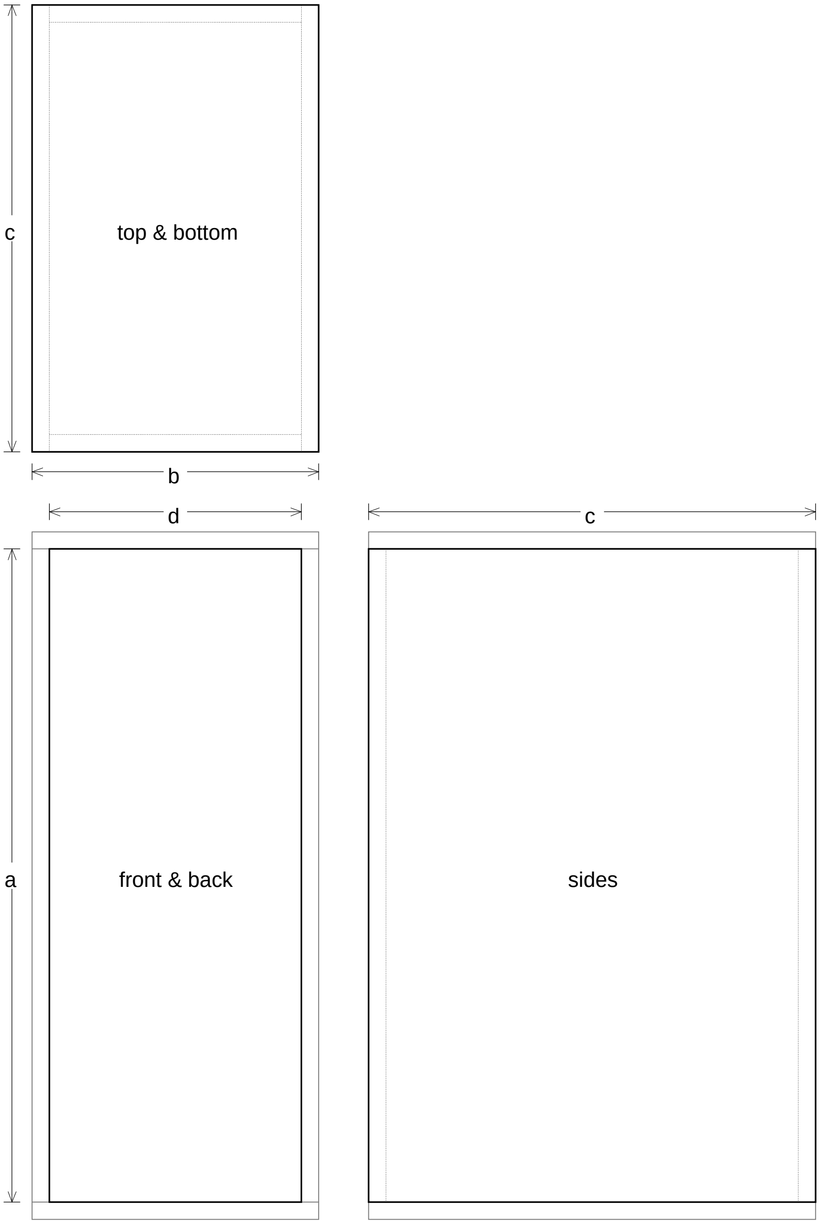


--*Description*--
Name: 755 c
Type: Standard one-way driver
--*Configuration*-**No. of Drivers = 1**
--*Driver Parameters*--
--*External Dimensions*--
A = 30 in
B = 12.5 inC = 19.5 in
--*Internal Dimensions*--
A = 28.5 in
B = 11 in
C = 18 in
--*Wall Thickness*--
Front = 0.75 in
Side = 0.75 in

Driver Properties

Fs = 66.23 Hz
Qms = 2.442
Vas = 42.68 liters
Xmax = 0.3 mm
P-Dia = 16 cm
Qes = 1.395
Re = 7.2 ohms
Le = 0.3 mH
Z = 7.23 ohms
Pe = 15 watts

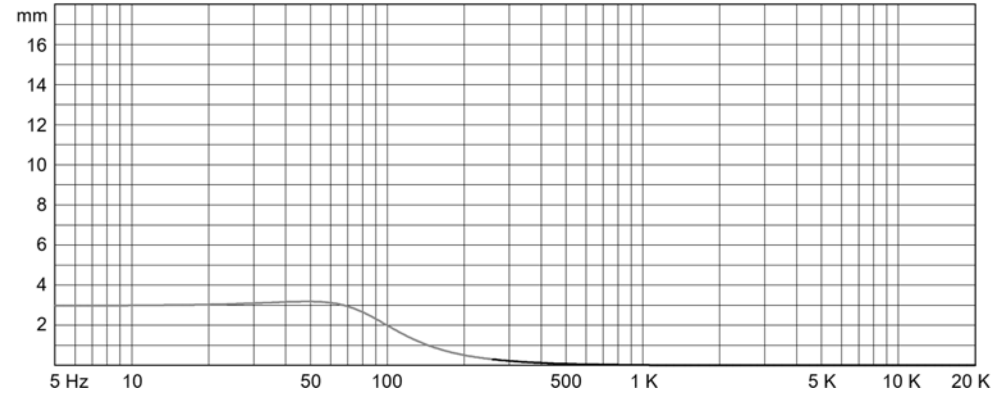
Box Parts



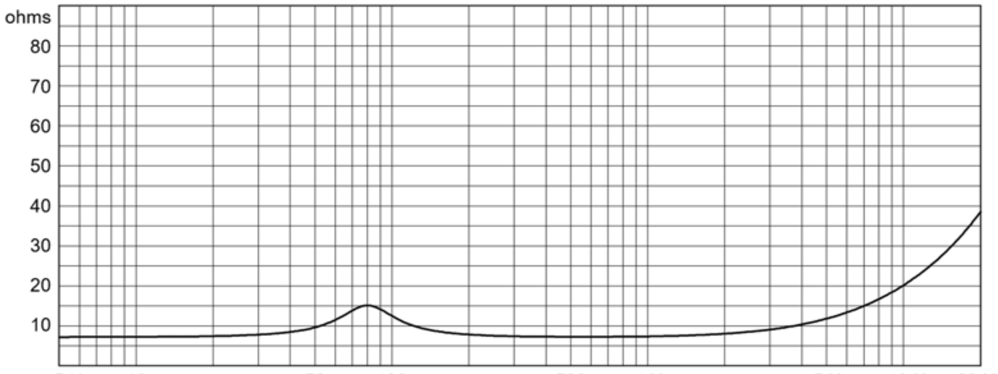
Box Shape: Square Prism
1 Top, 1 Bottom: depth (c) = 19.5 in   width (b) = 12.5, thickness = 0.75 in 1 Front, 1 Back: height (a) = 28.5 in   width (d) = 11, thickness = 0.75 in 2 Sides: height (a) = 28.5 in   depth (c) = 19.5, thickness = 0.75 in

--Driver Mounting--
Mounting: Front

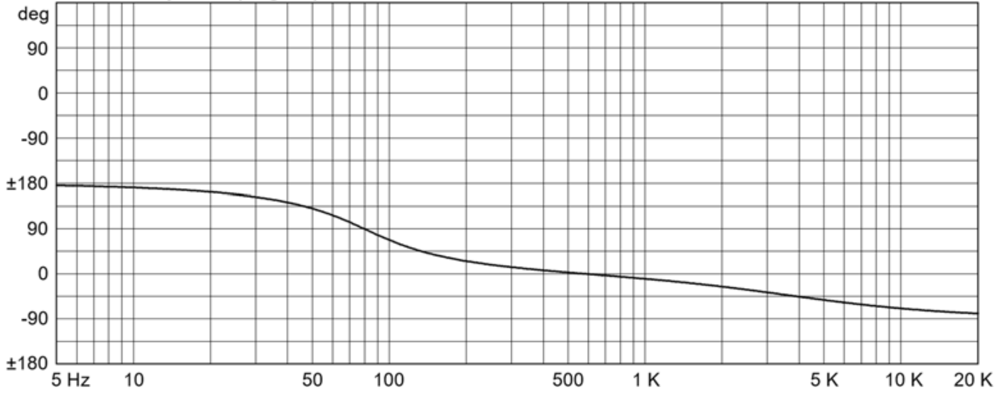
--Misc Objects Inside or Part of Box--
Object: object 1
No. of Objects: 1
Volume: 0.097 cu.ft (reduces box)
Shape: Known Volume (any shape)



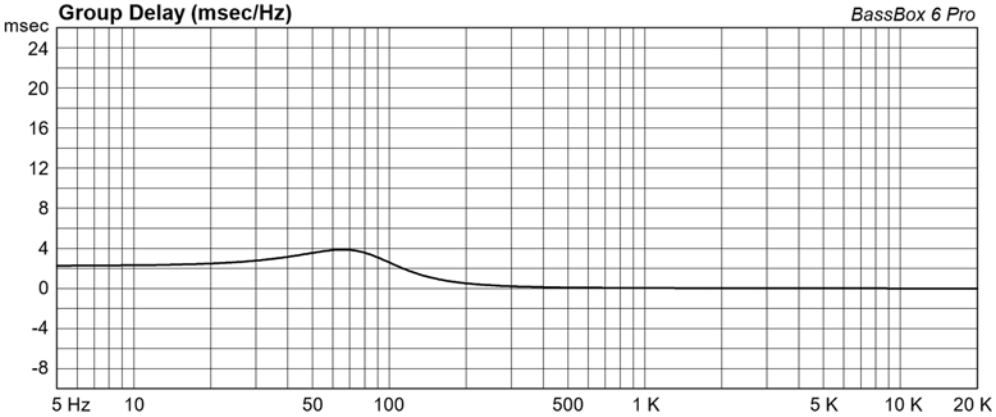
Cone Displacement (mm/Hz) with 15 watts



System Impedance (ohms/Hz)



Phase Response (deg/Hz)



Group Delay (msec/Hz)