

LOUDSPEAKER DESIGN CONSIDERATIONS FOR AMATEUR RADIO

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Steve Dick, K1RF

Listener fatigue

- ⦿ **Listener fatigue** (also known as listening fatigue) is a phenomenon that occurs after prolonged exposure to an auditory stimulus. include tiredness, discomfort, pain, and loss of sensitivity. Listener fatigue is not a clinically recognized state, but is a term used by many professionals. The causes for listener fatigue are still not yet fully understood

Source: http://en.wikipedia.org/wiki/Listener_fatigue

More on listener fatigue

- ⦿ Blockage of the ear canal, common in headphones, is thought to be a main contributing factor in listener fatigue due to physiology within the ear and central auditory system
- ⦿ When exposed to noise, the human ear's sensitivity to sound, or threshold of hearing, is decreased to protect the ear. Recovery from temporary threshold shifts take a matter of minutes and shifts are essentially independent of the length of exposure to the sounds. Also, shifts are maximal during and at frequencies of exposure.
- ⦿ Threshold shifts that result in long-term fatigue are dependent on level of sound and length of exposure.
- ⦿ Artifacts in audio material are uncomfortable for the ear, causing listeners to "tune out" and lose focus or become tired

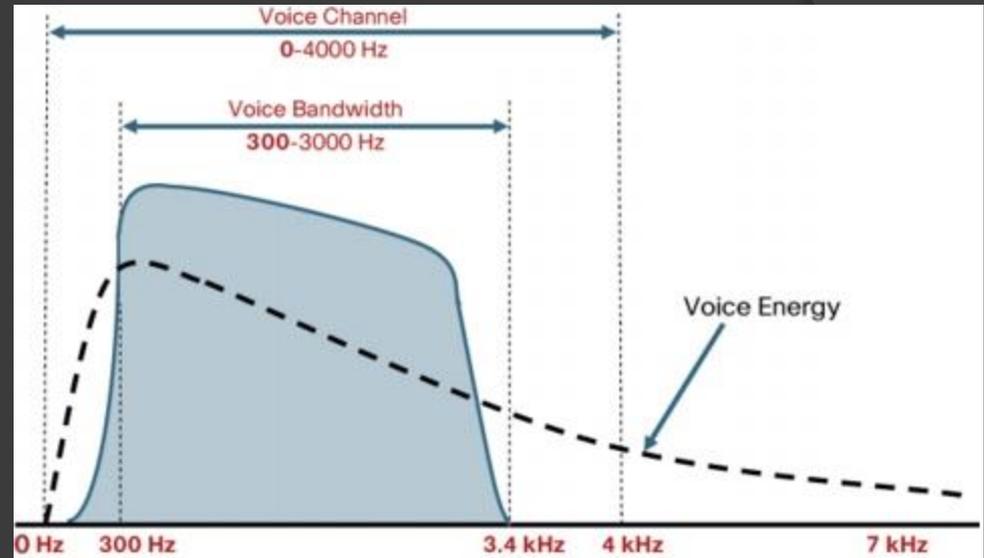
Some causes of listener fatigue in amateur radio

- ⦿ Distortions in the audio chain (demodulation, audio amplifier, speaker)
- ⦿ Listening to weak signals (low signal to noise ratios) for long periods of time
 - Receiver front end noise, atmospheric noise
 - Repetitive noise sources (Noise from appliances such as plasma T.V.s, computer switching power supplies, CFL and LED light bulbs, etc)
- ⦿ Listening to “communications quality” audio in voice modes, resulting in missing important speech components, especially at the low and high ends of the spectrum with narrowband filtering
- ⦿ Speech compression on transmit adds to listener fatigue because it is unnatural sounding and it raises the overall sound level
- ⦿ Many transceiver built-in speakers have inadequate low frequency response due to inadequate driver size and inadequate volume of air surrounding the driver. These are often included as an afterthought in transceiver design with most of the volume devoted to the electronics.

Try operating field day for a four hour shift for a bad case of listener fatigue!

Frequency content of voiced speech

- In telephony, (Toll quality), the usable voice frequency band ranges from approximately 300 Hz to 3400 Hz
- The voiced speech of a typical adult male will have a fundamental frequency from 85 to 180 Hz, and that of a typical adult female from 165 to 255 Hz.
- Thus, the fundamental frequency of most speech falls below the bottom of the "voice frequency" band as defined above. However, enough of the harmonic series will be present for the missing fundamental to create the impression of hearing the fundamental tone.
- The human ear can detect sounds from 20Hz from 20 KHz with the most sensitive region between 300 Hz and 10 KHz.



Sources:

http://en.wikipedia.org/wiki/Voice_frequency

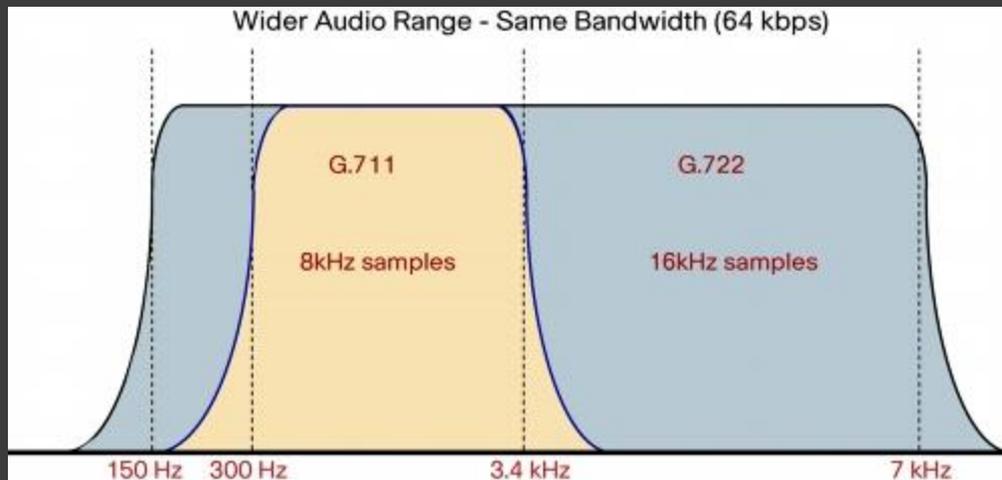
<http://www.uoverip.com/voice-fundamentals-human-speech-frequency>

http://www.cisco.com/c/en/us/products/collateral/collaboration-endpoints/unified-ip-phone-7965g/prod_white_paper0900aecd806fa57a.html

Most voice energy falls in the region 100 Hz to about 7 kHz

Wideband voice quality

- As the processing power of digital signal processor (DSP) chips increases, the ability for voice devices to perform an advanced voice-compression algorithm becomes easier and cheaper. Therefore, there has been a shift in the voice world to provide voice quality that is better than toll quality -- and the codec most commonly used to provide improved voice quality for voice over IP is the G.722 wideband codec.
- The wideband audio codec is not a new standard. In fact, the first recommendation for G.722 was published in 1988. A more recent G.722.2, also known as [AMR-WB](#) ("Adaptive Multirate Wideband") offers low bit-rate compressions (6.6 kbit/s to 23.85 kbit/s)



Sources:

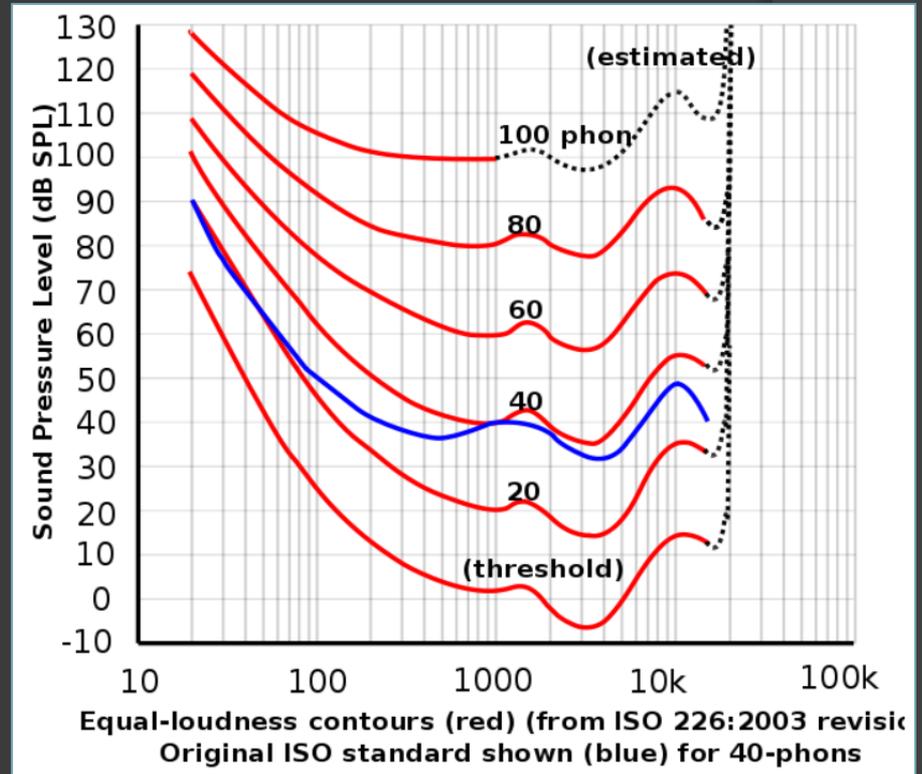
http://www.cisco.com/c/en/us/products/collateral/collaboration-endpoints/unified-ip-phone-7965g/prod_white_paper0900aecd806fa57a.html

<http://en.wikipedia.org/wiki/G.722>

G .722 Wideband audio codec includes 150 Hz to 7 kHz range

Equal Loudness Contours

- The ear does not have a flat acoustic response as a function of frequency.
- It's acoustic response varies with sound levels and flattens out as sound levels increase.

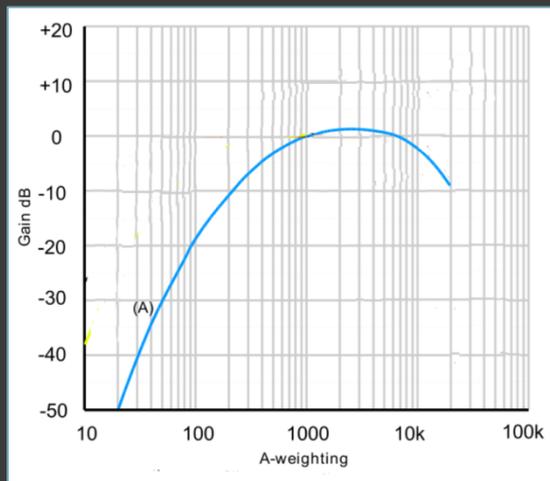


Source: http://en.wikipedia.org/wiki/Equal-loudness_contour

The ear is less sensitive to low frequencies and high frequencies below and above 1KHz, respectively. The curves “flatten out” as sound levels increase

Sound Pressure Level

- **Sound pressure level (SPL)** is a logarithmic measure of the effective sound pressure of a sound relative to a reference value
- The lower limit of audibility is defined as SPL of 0 dB
- A-weighting is applied to instrument-measured sound levels in effort to account for the relative loudness perceived by the human ear



A-weighting is approximately the inverse of the equal loudness contour at moderate to loud levels

Sound in air	Sound pressure level
Threshold of pain	130 dB
Vuvuzela horn at 1 m	120 dB(A)
Risk of instantaneous noise-induced hearing loss	approx 120 dB
Hearing damage (over long-term exposure, need not be continuous)	85 dB
Passenger car at 10 m	60-80 dB
EPA-identified maximum to protect against hearing loss and other disruptive effects from noise, such as sleep disturbance, stress, learning detriment, etc.	70dB
Handheld electric mixer	65 dB
TV (set at home level) at 1 m	60 dB
Washing machine, dishwasher	42-53 dB
Normal conversation at 1 m	40-60 dB
Very calm room	20-30 dB
Light leaf rustling, calm breathing	10dB
Auditory threshold at 1 KHz	0 dB

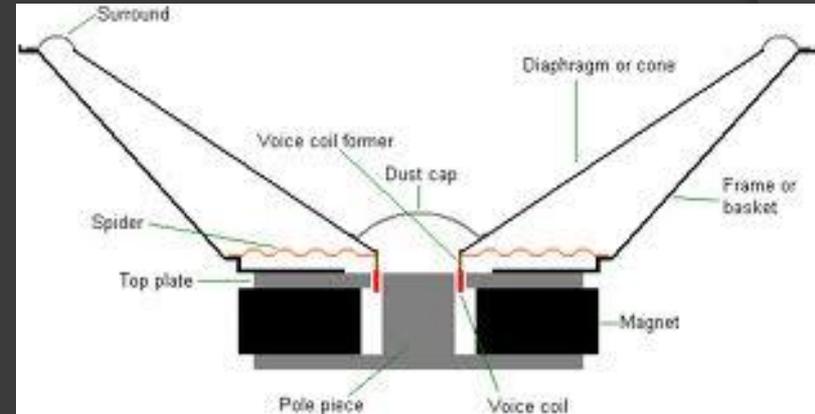
Source: http://en.wikipedia.org/wiki/Sound_pressure_level#Sound_pressure_level

For every 3 dBAs over 85dBA, the permissible exposure time before possible damage can occur is cut in half. 8 hours is the maximum time at 85dBA

Driver components

- **Magnet Structure** -- Two pieces of oppositely oriented magnets that produce a radial field from the inner to outer magnet
- **Voice Coil** -- Carries the current so that it is always moving in a plane perpendicular to the magnetic field; thus the force always acts on the same axis
- **Spider** – Rear suspension component providing restoring force
- **Cone** -- Produces pressure waves from its surface due to the oscillation of the spider
- **Basket** -- Holds the components together firmly, preventing motion in parts like the magnet structure
- **Surround** – front suspension component providing restoring force
- **Dust Cap** – Prevents “crap in the gap” - a clean speaker is a happy speaker :)

Voice coil and magnet structure are sometimes called the motor. A driver mounted in an enclosure is called a speaker.



Courtesy
<http://web.mit.edu/2.972/www/reports/speaker/speaker.html>

Driver design is both art and science

- Cone material – paper, treated paper, aluminum, fiberglass, polyester, poly-mica. Stiffness, density, damping affecting cone high frequency resonances
- Surround material – rubber, cloth, foam. Stiffness.
- Magnet – ferrite, neodymium. Size/efficiency
- Overhung, underhung voice coil (x_{max} , efficiency, distortion characteristics)
- Size of magnetic gap, length of voice coil (x_{max} , efficiency, distortion characteristics)
- Other exotic features (cooling, resonance control, etc)

Driver design is quite complex and tries to achieve characteristics suited for their intended purpose

Driver efficiency

- Super efficient speakers can provide efficiencies as high as 4%, corresponding to an SPL of +98 dB at 1 watt and 1 meter.
- The majority of drivers are even less efficient. Drivers have become less efficient generally since the 1960s as high power solid state amplifiers (e.g. 150 watts, compared with the 15 watts that was considered large from a tube amplifier) have become available at a reasonable price and made it practical for drivers to trade efficiency for lower distortion.
- Nowadays a driver that produces an SPL of +85dB at 1 meter from a 1 watt input is 0.2% efficient, not at all unusual.
- An inefficient driver (SPL in the region of 80-85dB at 1W/1M should be driven by an amplifier capable of 8 watts output or more with low distortion.
- Inefficient drivers are not all bad – they typically have a larger throw, providing less distortion at low frequencies.

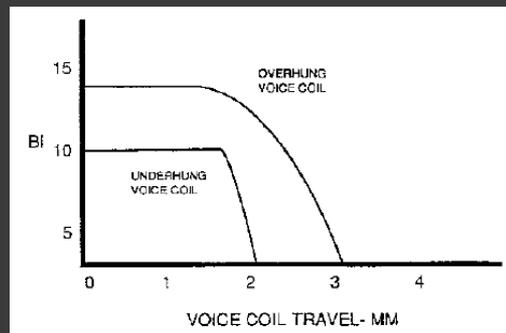
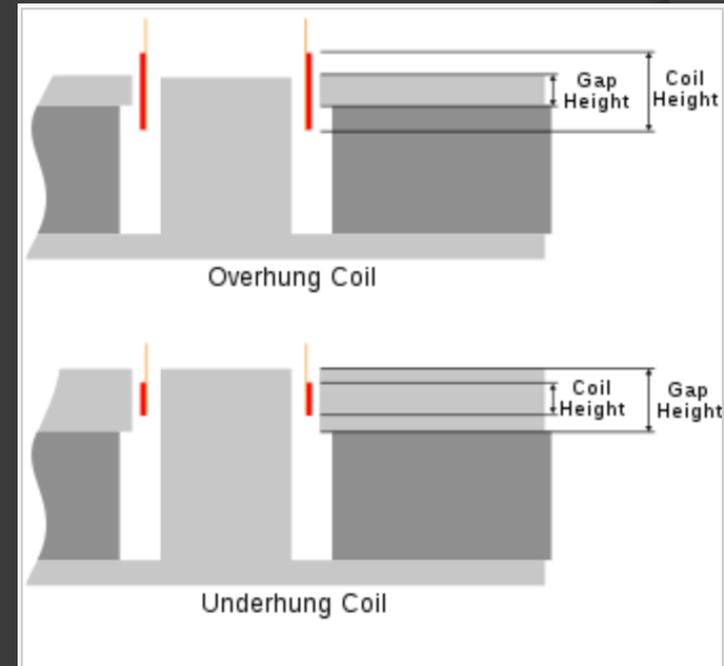
Overhung vs. Underhung Voice coils

Overhung coil (most common)

- Used in the majority of drivers
- Coil height is greater than the gap's height.
- Higher coil mass than underhung
- Soft non-linearity as the coil exceeds limits.

Underhung coil

- Used in high-end drivers
- Gap's height is greater than the coil's height.
- Lower coil mass than overhung
- Hard non-linearity as the coil exceeds limits.



Source:
Loudspeaker
design
cookbook

Light grey is soft iron, dark grey is permanent magnetic material and the coil is in red.

Source: http://en.wikipedia.org/wiki/Voice_coil

Overhung coil is most common as it provides better efficiency for a given magnet size and has soft nonlinear at the expense of higher voice coil mass

So what driver(s) to use?

- ⦿ Must include the range ~ 100Hz to 7 KHz for high quality voice.
- ⦿ Don't need multiple drivers (woofer and tweeter or woofer, midrange, and tweeter)
 - Difficult to match SPL levels between multiple drivers, and required crossover circuits add losses and additional delay/phase shifts
 - The tweeter, found in most hi-fi speakers, provide high frequency performance you don't need in an amateur radio application, which adds undesired high frequency noise

Recommendation: Use a single high efficiency, full range driver for an amateur radio speaker.

The Thiele-Small Parameters

- ⦿ The loudspeaker parameters were first described by Thiele in 1961, but were not accepted widely until after they were republished in the Journal of the Audio Engineering Society in 1971, and Small, over the next three years, published a series of papers that expanded them and made them much more understandable and useful.
- ⦿ Over the last thirty years, they have been used widely, almost universally, to characterise loudspeaker drivers and thus facilitate the design of loudspeaker systems.

Thiele-Small Parameters

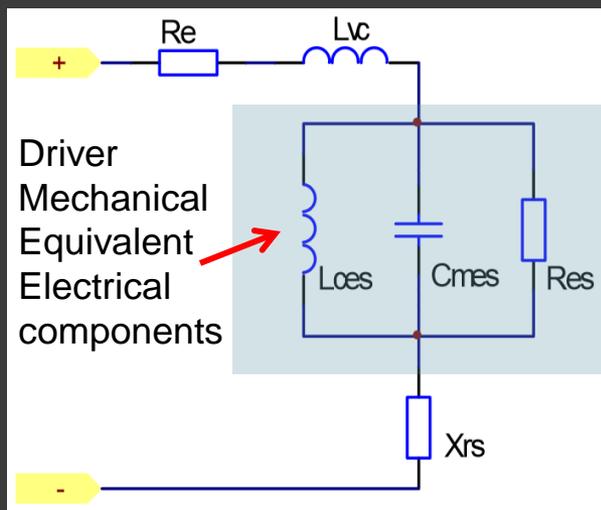
- ⦿ The following main parameters characterize the performance of a loudspeaker driver and are used to calculate its performance when it is mounted in an enclosure or box.
- ⦿ f_s the resonance frequency of the driver in Hz
- ⦿ Q_E the 'electrical' quality factor, the ratio of the d.c. resistance of the voice coil to reactance at resonance of the drivers motional impedance. It is a pure, dimensionless, number
- ⦿ Q_M the 'mechanical' quality factor, the ratio of the shunt resistance of the driver's motional impedance to its reactance at resonance, another pure number. In some early publications, Thiele has called this parameter Q_A for 'acoustical'.
- ⦿ The Q values, or quality factors, affect the damping of the driver around its resonance. The higher the Q's the more the frequency response at resonance will peak compared with the in-band response at higher frequencies. If the Q's are too low the frequency response will sag around resonance

Thiele-Small Parameters cont'd

- ⦿ The “total” quality factor, Q_t is: $(Q_E \times Q_M)/(Q_E + Q_M)$, analogous to the parallel resistance formula, when driven from a low impedance source.
- ⦿ V_{AS} , the volume of air equivalent to the acoustical compliance of the driver. It may be specified in litres, cubic feet or cubic inches. This parameter V_{AS} affects the response through its ratio with V_b , the volume of the box that the driver is mounted in.

f_s , Q_E , Q_M , and V_{AS} along with V_B , the volume of the box, dictate the smoothness and shape of low frequency response that is obtained from a loudspeaker driver/box combination

Simplified Driver Model



R_e = D.C. resistance of voice coil

L_{vc} = inductance of voice coil

L_{ces} = suspension compliance equivalent inductance

C_{mes} = cone mass equivalent capacitance

R_{es} = suspension losses equivalent resistance

X_{rs} = radiation impedance representing voltage drop resulting from sound output

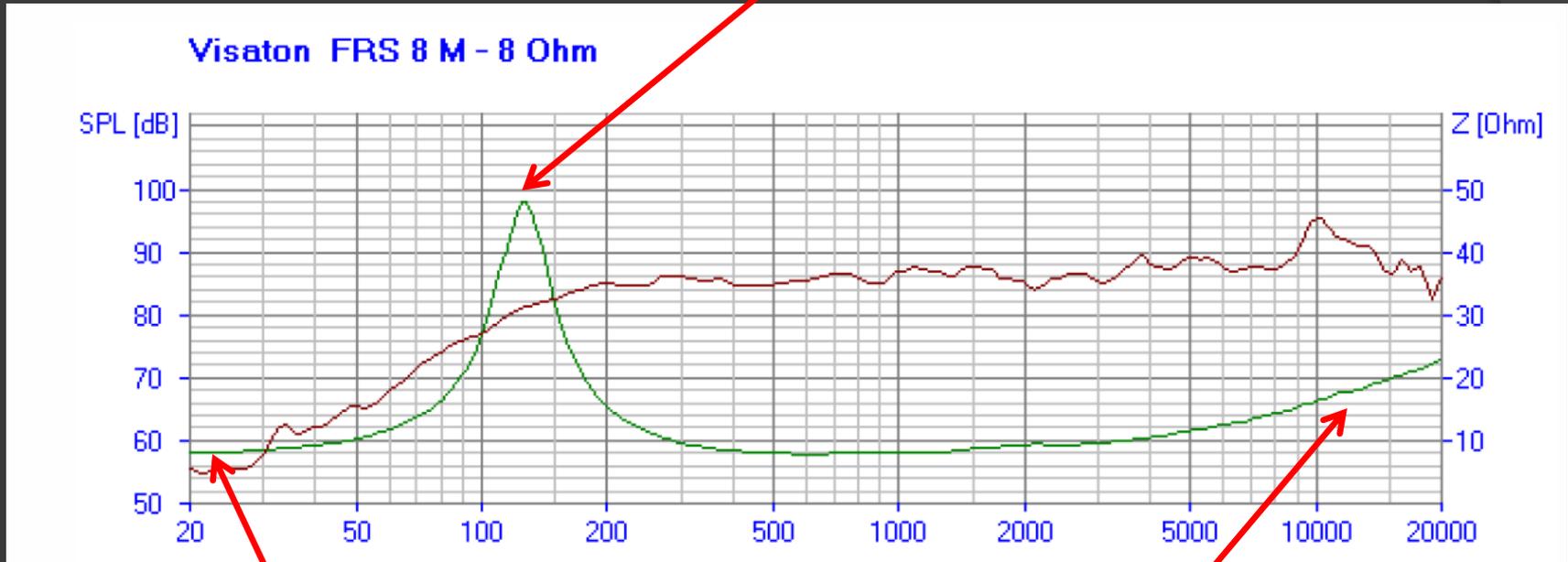
Source: http://www.transparentsound.com/measurements/Tomi_Engdahl.pdf

An 8 ohm driver, for example, is not 8 ohms!! It's D.C. resistance is typically lower, maybe 6.5 ohms and its impedance varies with frequency, including a huge resonant peak!!

Impedance plot of typical 8 ohm driver

Impedance peak is a function of Q_{ms} .

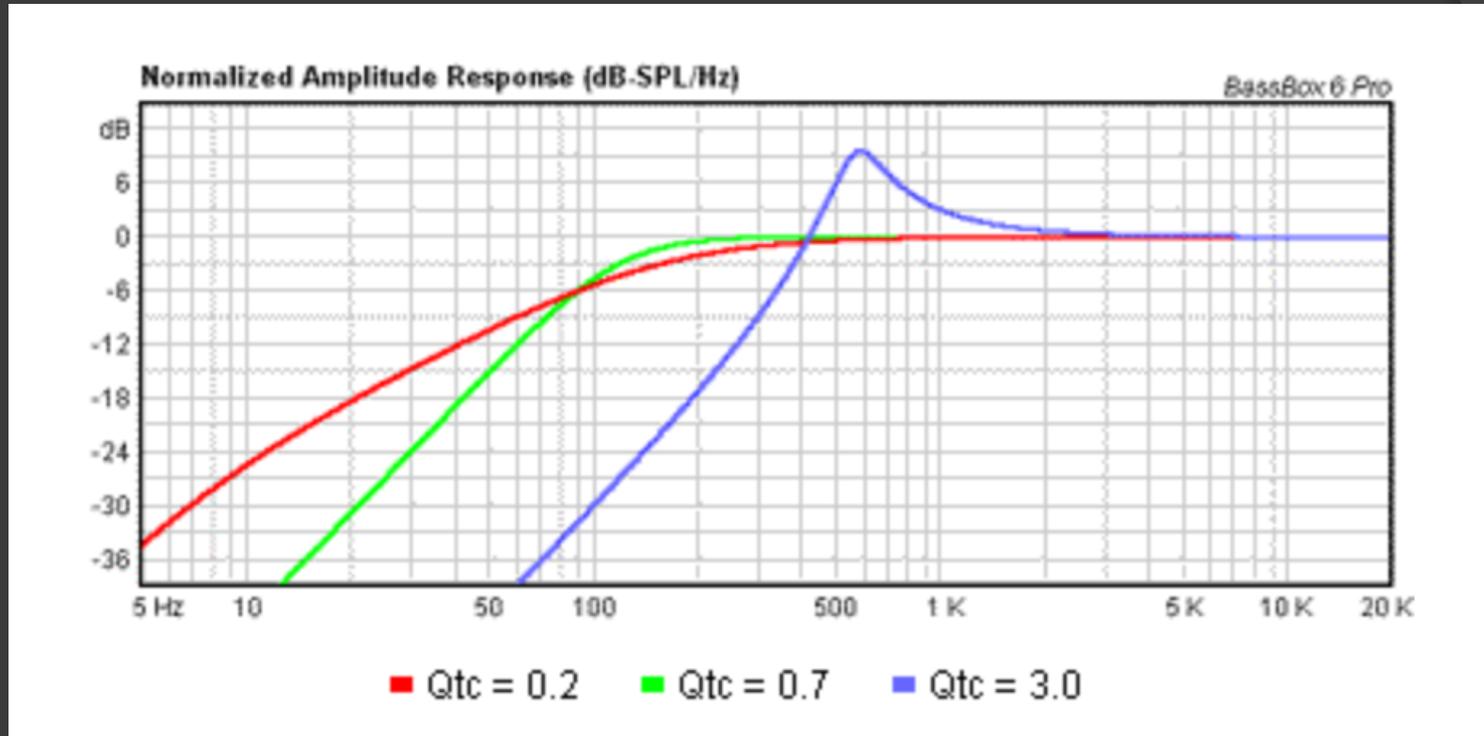
In this example, impedance at resonance ~ 48 ohms



D.C. resistance (R_e) = 7.2 ohm

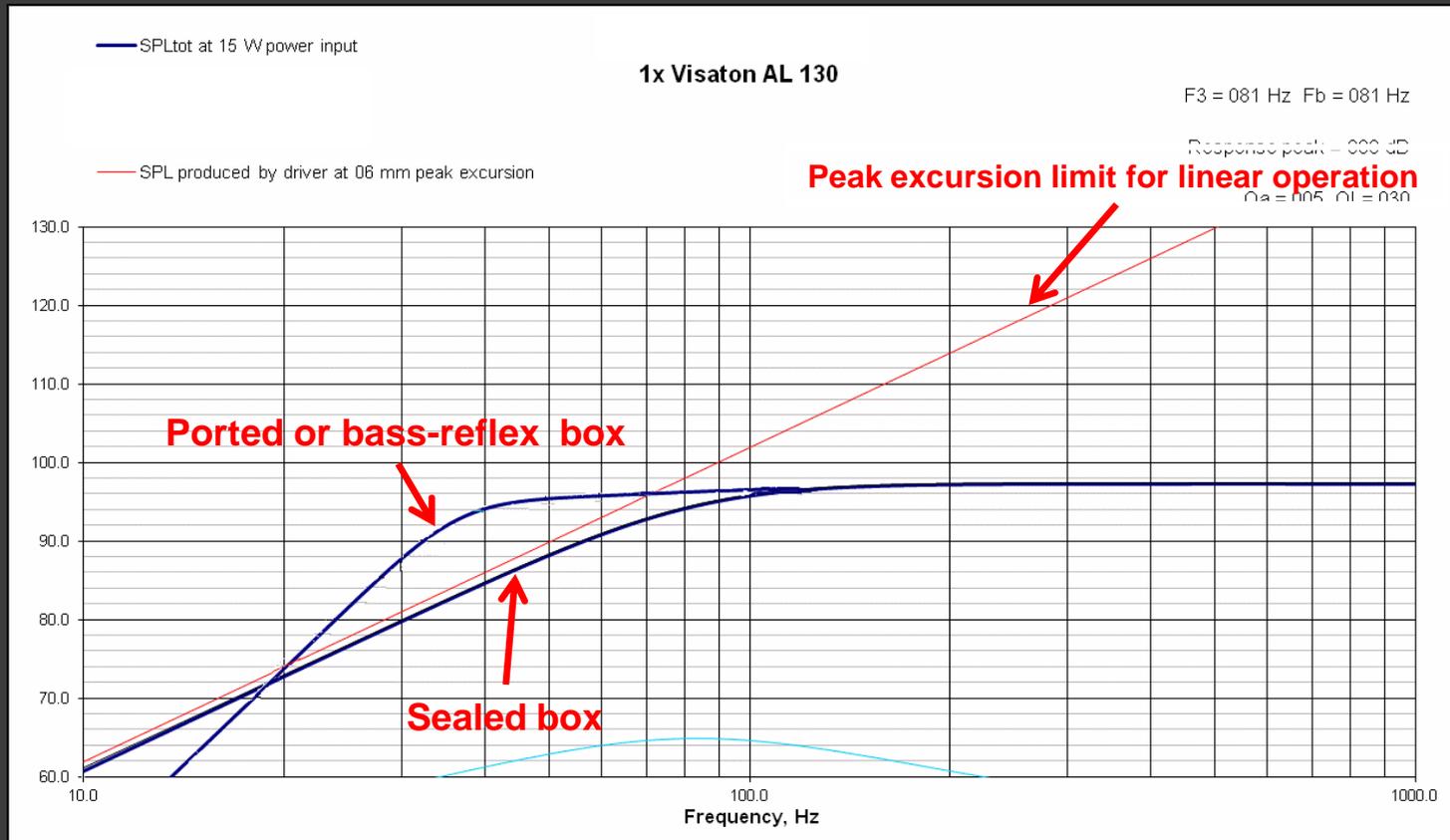
Impedance increasing due to voice coil inductance. Causes some amplifiers to oscillate. Can be compensated for with a series R-C across driver, known as a Bucherot Cell or a Zobel Network. This flattens the impedance curve

Effect of Q_{tc} on low frequency response



- **$Q_{tc} = 0.7$: response is "maximally flat", meaning that the response stays level for as long as it can before dropping off**
- $Q_{tc} = 0.2$: Box is much too large. Extends low frequency response but drops off sooner
- $Q_{tc} = 3$: Box much too small – have large 6dB response peak causing ringy sound at the resonant peak and low frequency response drops off much too soon.
- Can use active compensation in an amplifier chain with a Linkwitz transform circuit.

Sealed box vs. Ported box response



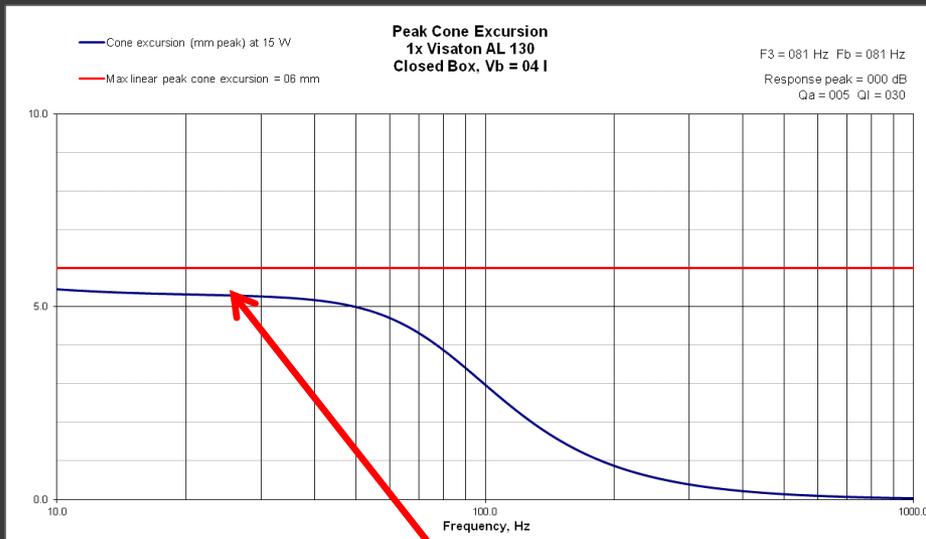
Sealed box



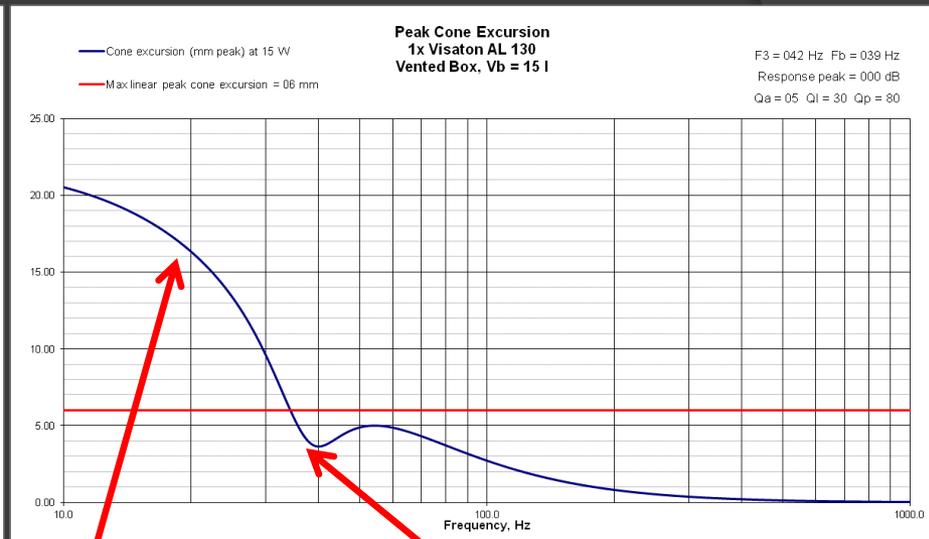
Ported box

- Ported box has lower frequency capability for same driver vs sealed box
- Sealed box rolls off at about 12 dB/octave. Ported box rolls off at about 24dB/octave. Peak excursion limit more easily exceeded for ported box.

Representative Sealed box vs ported box driver cone excursion behavior



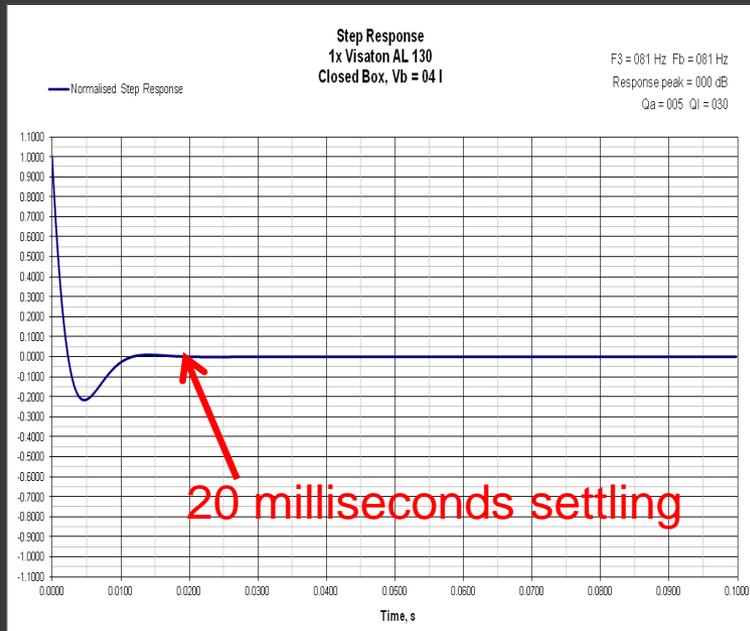
Excursion well-controlled at low frequencies. Air in sealed box acts as a spring and constrains speaker excursion. Typically no special filters required.



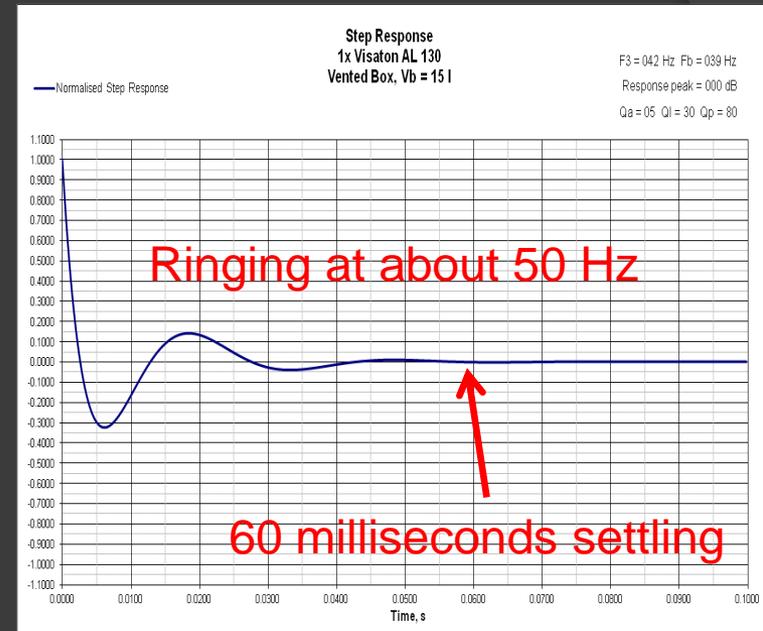
Excursion dip at port tuned frequency

Driver Cone unconstrained below port tuned frequency. Damage can result. High pass filter usually required. Simple HPF is a series capacitor

Sealed box vs. ported box response to a step



Sealed box



Ported box

- Sealed box settles much faster (more responsive) at low frequencies, by a factor of about 3 in this example.
- Ported box rings longer due to resonant effect of the port.
- Not that important for amateur radio voice but could affect high speed CW communication.
- A dot length at 40wpm ~ 30 milliseconds

Sealed box vs. ported box pros and cons

Sealed box

- **Pros:**
 - Well-controlled cone excursion at low frequencies
 - Smoother frequency rolloff of 12 dB/octave
 - Smoother phase response at low frequencies
 - Faster settling at low frequencies
 - Simpler enclosure design
 - Smaller enclosed volume required
- **Cons:**
 - higher low frequency limit

Ported box

- **Pros:**
 - Lower low frequency limit
- **Cons:**
 - Uncontrolled cone excursion below tuned port frequency can cause damage unless high pass filter used
 - Sharper frequency rolloff of 24 dB/octave
 - Rougher phase response at low frequencies
 - Slower settling at low frequencies
 - More complex enclosure design
 - Larger enclosed volume required

Recommendation: Use a sealed box for amateur radio speaker. We don't want or need the very low frequency response of a ported box for a properly selected/sized driver.

Acoustic Damping

- Acoustic damping material is material that converts acoustic power to heat.
- Acoustic damping provides three benefits in a speaker design:
 - Increases the effective volume of an enclosure by as much as 20%
 - Greatly reduces or eliminates cabinet resonances
 - Lowers system “ Q_{tc} ” which reduces the size of the low frequency response peak if Q_{tc} is too high
- Typical materials used: Open cell foam, glass or plastic spun fibers, spray-on damping materials, etc



Photos courtesy
Parts Express

Recommendation: Use of acoustic damping material is almost always beneficial

Representative transceiver audio output specifications

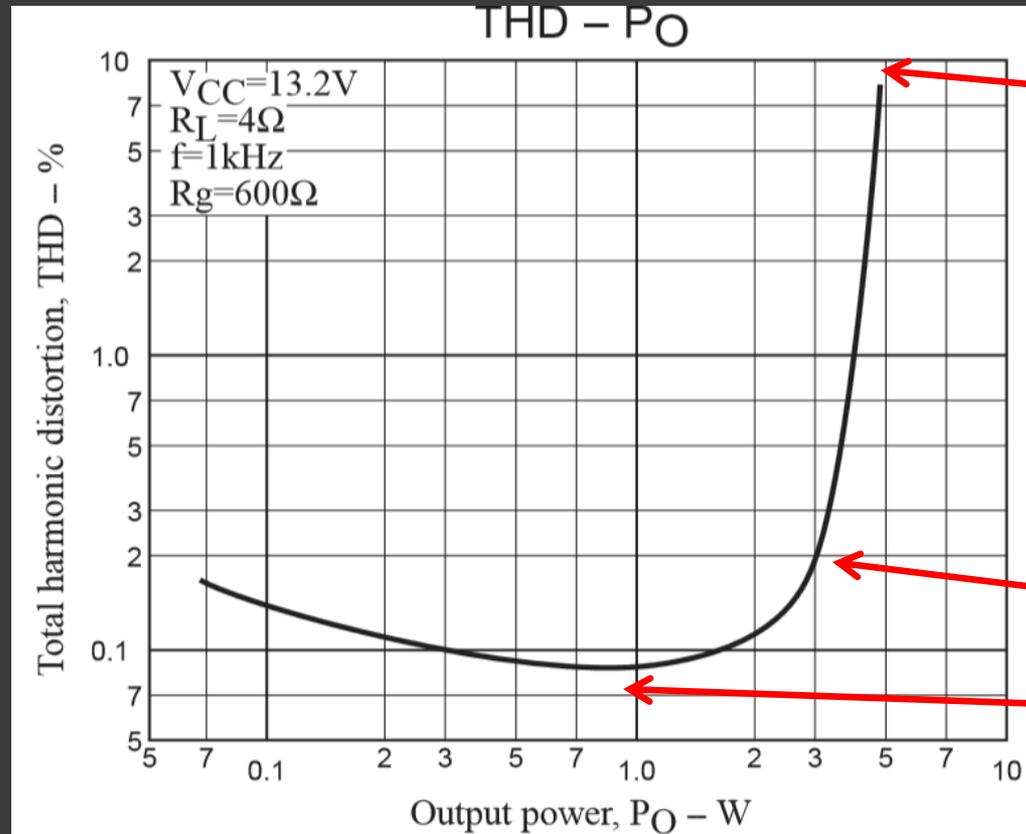
Transceiver	Power Output	Total Harmonic distortion	load
Elecraft K3	2.5W per channel	Typical 10%	4 ohm
Yaesu FT950	2.5W	10% into 4 ohm	4 -8 ohm
Icom IC756 Pro 3	2W minimum	10%	8 ohm
Icom IC7200	2W minimum	10% into 8 ohm	4-8 ohm
Tentec Eagle	2W into 4 ohm	<3%	4 ohm
Kenwood TS590S	More than 1.5W	10%	8 ohm

Most transceivers have high distortion (10%) at relatively low maximum power output (2 to 2.5 watts.)

Recommendation: Use a high efficiency speaker (>85dB SPL at 1 Watt at 1 meter) or use a more inefficient speaker with an external audio amplifier to reduce output amplifier distortion

Representative transceiver audio amplifier distortion

LA4425A class AB amp used in IC7200



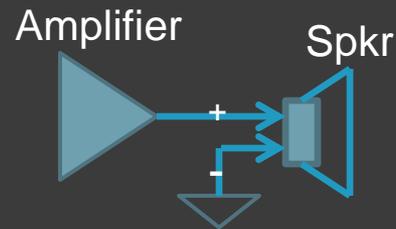
10% distortion at 5W

<0.2% distortion below 3W

Sweet spot at 1W out:
<0.1% distortion

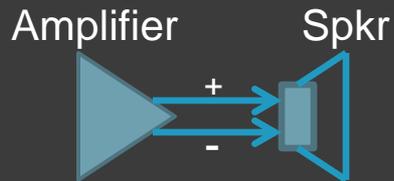
Distortion rises rapidly above ~ 3 watts

Audio amplifiers: Single ended vs Bridge-Tied Load (BTL)



Single-ended Amplifier

For a 13.8V power supply, let's assume the amplifier can swing from 0.9V to 12.9V to stay in its linear region. That's 12V peak to peak or 6 volts peak. For an 8 ohm speaker, maximum power out is $V^2/8 = (6 * .707) * (6 * .707)/8 = 36/16 =$ **2.25 Watts**. For a 4 ohm speaker, we can get 4.5 watts. This is pretty independent of the particular amplifier device.



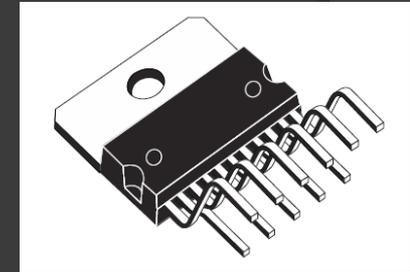
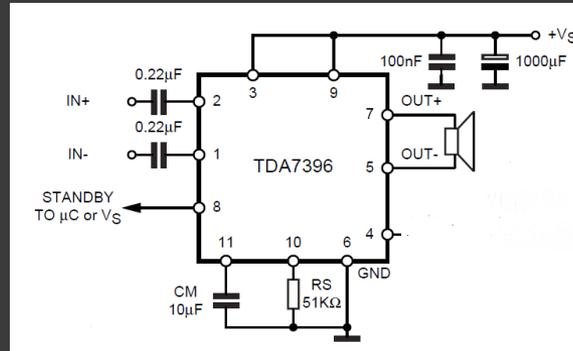
Bridge-Tied Load (BTL)
Amplifier

For a 13.8V power supply, let's assume each amplifier output can swing from 0.9V to 12.9V to stay in its linear region. The two outputs swing in opposite directions. That's 24 volts peak to peak or 12V peak. For an 8 ohm speaker, Maximum power out = $12 * 12 / 16 =$ **9 watts**. For a 4 ohm speaker, that's 18 watts.

A BTL amplifier provides 4X the power output before distorting compared to a single-ended output!!!

Ideas for BTL low distortion amplifiers

- ◉ STM TDA7396 45W BTL class AB car radio amp \$5.04. Digikey P/N 497-10503-ND. Amplifier cost <\$15.00 for all parts, Very overvoltage tolerant, short circuit proof



- ◉ PAM8610 2x10W Class-D Audio Amplifier Board 7-15VDC power, \$11.80 Parts Express # 320-604 and use one channel.



Best used in a shielded box with EMI filtering on speaker leads to minimize EMI

- ◉ Lepai 2020A+ 2X20W Class T amp plus power supply wall wart. Parts Express # 310-300 \$19.98 special



Class AB amplifier recommended for no EMI.

Build your own small, good performance, nice looking sealed box weather resistant speaker for about \$55.00!!

Item	Qty	Vendor	Description	Distributor	Distributor P/N	Unit cost	Total cost
1	1	Visaton	SL87 FE-8 full range driver*	www.parts-express.com	292-614	\$17.83	\$17.83
2	1	mcmaster.com	Speaker grille/fan guard (optional)**	mcmaster.com	19155K95	\$1.24	\$1.24
3	1	Sonic Barrier	1/2 inch self sticking acoustic foam	www.parts-express.com	260-520	\$9.97	\$9.97
4	1	Parts Express	round speaker terminal cup spring type	www.parts-express.com	260-294	\$1.25	\$1.25
5	1	Hammond	1550WFBK black powdercoat die cast aluminum chassis 6.74X4.76X3.98	www.digikey.com	HM1217-ND	\$20.32	\$20.32
				www.mouser.com	546-1550BK		
6	1		Switchcraft MD5L2A mono phone jack 3.5mm	www.mouser.com	502-MD5L2A	\$2.51	\$2.51
7	4	parts express	rubber cabinet feet .88" X.31"H	www.parts-express.com	260-7706	\$0.42	\$1.68
						Total	\$54.80

* A good inexpensive driver if used with amplifier is VIFA TC9FD-18-08 3-1/2" for \$11.95 SPL 85.7dB

** A compatible black plastic grille available only special order: Visaton [GRILLE FR 87](#)

- Impedance: 8 ohms full range driver, SPL: 86.9dB (simulated in UniBox)
- Qtc = 0.8, close to ideal for flat low frequency response (simulated in UniBox)
- 3db lower cutoff frequency: 138 Hz (simulated in UniBox),
- frequency response 75Hz-18KHz
- Weather resistant in humid environments and for outdoor use.

Build your own DSP speaker

- See QST – November 2011
- Updates at <http://www.kg4jjh.com/dspspeaker.html>



- Powered speaker in a Hammond enclosure
- Uses a DSP PC board to reduce noise and tones.
- Listen for yourself on the DSP performance at the author's website, listed above
- Note: the enclosure selected is a nice sealed box with front panel gasket, powdered black paint for about \$20.00 from Digikey or Mouser
- The DSP PC board is not inexpensive at a cost of about \$150

Demo with UniBox showing effect of cabinet size and damping

Examples of good commercial speakers for amateur radio use

Avantone Passive MixCube Monitors In Black



SPL / Sensitivity

93dB @ 1w / 1 meter

Cabinet

sealed / 18mm MDF / Dacron acoustical stuffing

Frequency Response 90Hz - 17,000Hz

Impedance: 8 ohms

Dimensions

6 1/2" x 6 1/2" x 6 1/2" in)

Driver

5.25" cast aluminum frame

~ \$149.00



Dayton Audio B652

(Parts Express 300-652)

SPL/Sensitivity 87dB 1W/1M

Cabinet: Sealed 2-way

Frequency response 70-20000 Hz. **Impedance** 6 ohms

Dimensions 11-13/16" H x 7-1/16" W x 6-7/16" D

Drivers: 6-1/2" polypropylene cone woofer and a 5/8" polycarbonate ferrofluid cooled dome tweeter

(If possible, shape the Rx audio to cut high frequency response)

\$39.80/pair

Or build your own high efficiency speaker <\$35 with an MDF or plywood cabinet

Volume: lts mm³ cm³ in³ ft³ lts

 Click and drag the edges of the speaker box, or type in new values in the width, height, & depth fields.

Dimensions of each panel
 Option 1 Option 2 Option 3

	Width	Height
Front:	<input type="text" value="6.5"/> in	<input type="text" value="6.5"/> in
Back:	<input type="text" value="6.5"/> in	<input type="text" value="6.5"/> in
Left:	<input type="text" value="5.5"/> in	<input type="text" value="5.5"/> in
Right:	<input type="text" value="5.5"/> in	<input type="text" value="5.5"/> in
Top:	<input type="text" value="6.5"/> in	<input type="text" value="5.5"/> in
Bottom:	<input type="text" value="6.5"/> in	<input type="text" value="5.5"/> in

1/2 inch MDF cabinet

Volume: lts mm³ cm³ in³ ft³ lts

 Click and drag the edges of the speaker box, or type in new values in the width, height, & depth fields.

Dimensions of each panel
 Option 1 Option 2 Option 3

	Width	Height
Front:	<input type="text" value="6.5"/> in	<input type="text" value="6.5"/> in
Back:	<input type="text" value="6.5"/> in	<input type="text" value="6.5"/> in
Left:	<input type="text" value="5.56"/> in	<input type="text" value="5.56"/> in
Right:	<input type="text" value="5.56"/> in	<input type="text" value="5.56"/> in
Top:	<input type="text" value="6.5"/> in	<input type="text" value="5.56"/> in
Bottom:	<input type="text" value="6.5"/> in	<input type="text" value="5.56"/> in

1/2 inch plywood cabinet

Item	Description	Vendor	Vendor P/N	Qty	Unit cost	Total cost
1	Dayton Audio PA130-8 5" full range driver	Parts Express	295-010	1	17.98	17.98
2	Round speaker terminal cup	Parts Express	260-294	1	1.25	1.25
3	rubber feet	Parts Express	260-7706	4	0.42	1.68
4	1/2 inch acoustic foam 18" X 24"	Parts Express	260-520	1	9.97	9.97
5	#6 X 3/4" DEEP THREAD PAN HEAD SCREWS BLACK 100 PCS.	Parts Express	081-435	1	2.9	1.68
6	1/2" X 2 ft X 4 FT MDF panel	Home Depot	1508108	1	8.89	1.68
					Total	34.24

Plus wood glue,
Silicone sealant,
Finishing matl's

SPL 90dB 1W/1M, 90-15K frequency response, $f_{3db} = 144\text{Hz}$ simulated in UniBox, $Q_{tc} = 0.698$, simulated in UniBox

Speaker box designer/calculator: <http://www.diyaudioandvideo.com/Calculator/Box/>

Summary: speaker for amateur radio use

- Use a sealed cabinet. Good material is $\frac{1}{2}$ inch or $\frac{3}{4}$ inch MDF for its density and low resonances. Plywood also OK
- Use a single full range driver with high efficiency (>85 dB SPL covering a frequency range of at least 100 Hz to 7 KHz. Use 3 to 5 inch size. 5 inch preferred for ease of obtaining best low frequency response and highest efficiency with reduction of frequencies > 7 KHz.
- Use acoustical damping material in the cabinet to lower system “Q”, reduce resonances, and increase effective enclosure volume
- If the rig permits, use a 4 ohm speaker rather than 8 ohm for twice the power output before distortion sets in
- For homebrew external audio amplifiers (class AB, D, or T) running from 13.8V power, use a bridge-tied load amplifier configuration rather than a single ended output configuration for 4X the power output before distortion sets in, power dissipation permitting. Class AB preferred for no EMI. Class D or T require careful shielding and filtering
- Avoid foam surrounds for longest driver life. Use cloth or rubber surrounds.
- Be creative in finding ready-made speaker cabinets if you don't want to build your own

Useful Links/resources

- Speaker basics – a great overview: <http://www.ht-audio.com/pages/SpeakerBasics.html>
- Nice speaker tutorial: <http://www.bcae1.com/speaker.htm>
- Detailed speaker and cabinet tutorial:
http://www.hometheaterhifi.com/volume_5_2/cmilleressayporting.html
- In-depth speaker design tutorial:
https://engineering.purdue.edu/ece103/LectureNotes/SRS_Loudspeaker_Parameters.pdf
- The Thiele/Small parameters: <http://en.wikipedia.org/wiki/Thiele/Small>
- More on Thiele/Small parameters: <http://www.hornlautsprecher.net/Dokumente/Grundlagen/Tiele-Smal-LSPRMTRS604.htm>
- Measuring Thiele/Small loudspeaker parameters: <http://sound.westhost.com/tsp.htm>
- Compensating circuits:
 - Bucherot Cell (series R-C across driver to flatten impedance curve at high frequencies): http://en.wikipedia.org/wiki/Boucherot_cell
 - Zobel Network (general case of flattening an impedance curve) : http://en.wikipedia.org/wiki/Zobel_network
 - The Linkwitz Transform (to lower the low frequency peak and improve low frequency response) : <http://sound.westhost.com/linkwitz-transform.htm>
- Free Software tools:
 - UniBox – Unified box model for loudspeaker design free for personal use:
<http://audio.claub.net/software/kougaard/ubmodel.html>
 - ajesigner .com speaker design freeware: <http://ajdesigner.com/speaker/index.php>
 - Speaker box designer/calculator: <http://www.diyaudioandvideo.com/Calculator/Box/>
- KG4JJH DSP Speaker: <http://www.kg4jjh.com/dspspeaker.html>
- Speaker cabinet construction:
 - MDF tutorial: <http://www.diyaudioandvideo.com/FAQ/MDF/>
- ESSB Hi-Fi audio: <http://www.nu9n.com/home.html>