LOUDSPEAKER DESIGN CONSIDERATIONS FOR AMATEUR RADIO

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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

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

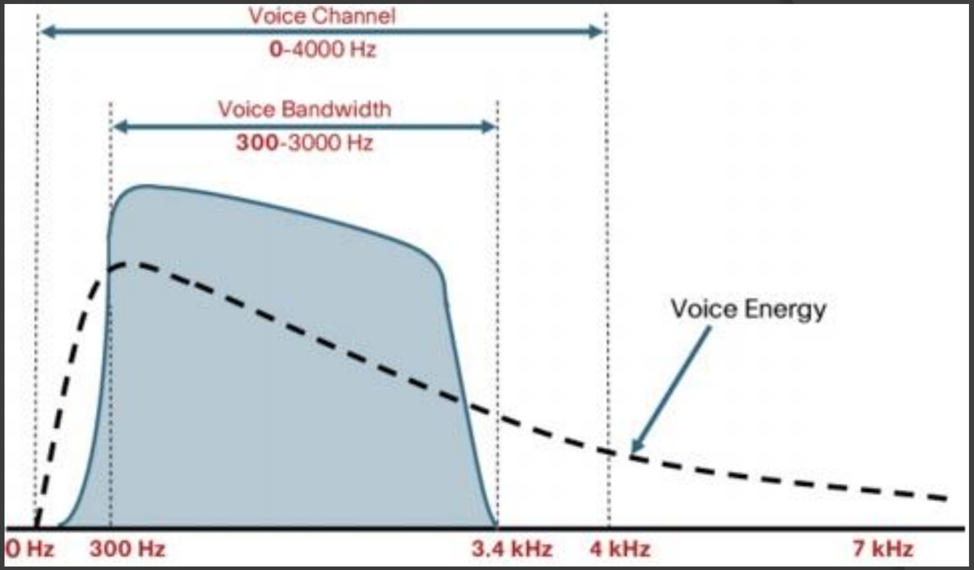
Some causes of listener fatigue in amateur radio

- 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)
  - Poor AGC performance in the presence of noise in most modern (post 2003) DSP-based receiver I.F. strips. See Rob Sherwood's presentation
- 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.
- Poor, relatively low power, single ended output amplifiers in most modern transceivers, resulting in high distortion even at relatively low volumes. Odd harmonics and intermodulation distortion are particularly bad in some radios.

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:

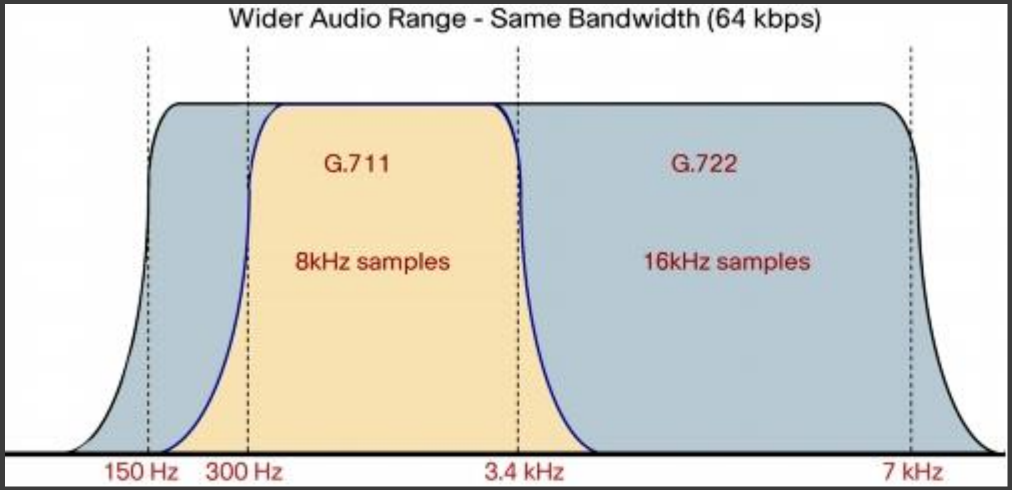
http://en.wikipedia.org/wiki/Voice_frequency
http://www.uoverip.com/voice-fundamentals-human-speech-frequency

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, But most SSB amateur transmitters remove low frequencies below 300 hz

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

Also see Polycomm whitepaper "The effect of bandwidth on speech intelligibility"

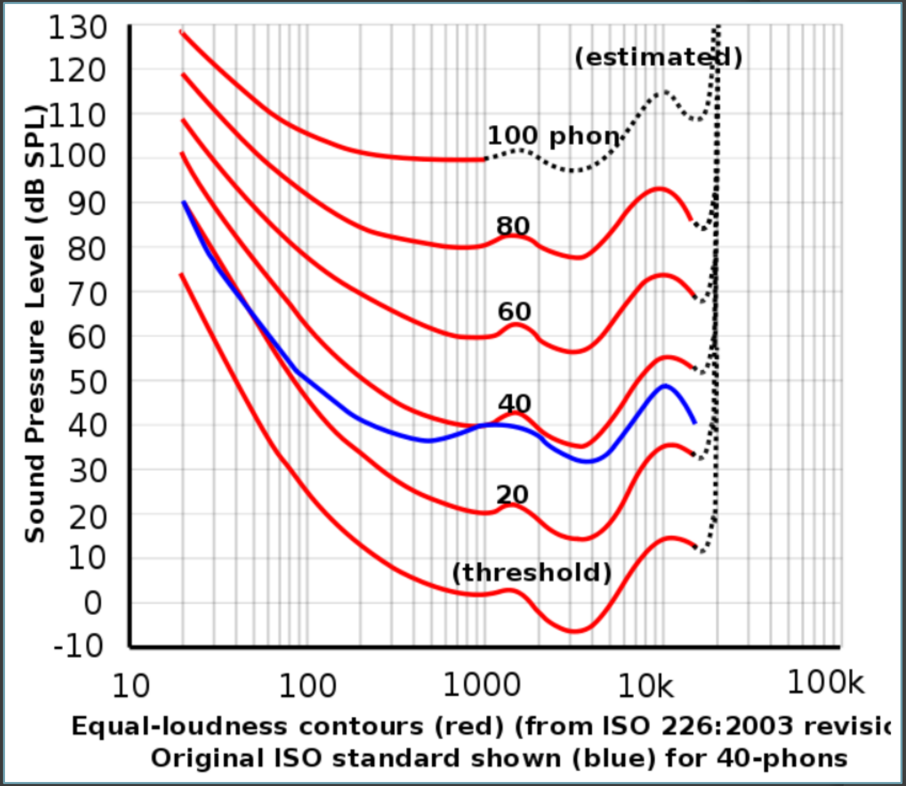
and ITU mode designations for SSB and ESSB

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

Standard SSB is 300 Hz ~ 2.7 kHz at 6dB points (ITU 2K40J3E)

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.

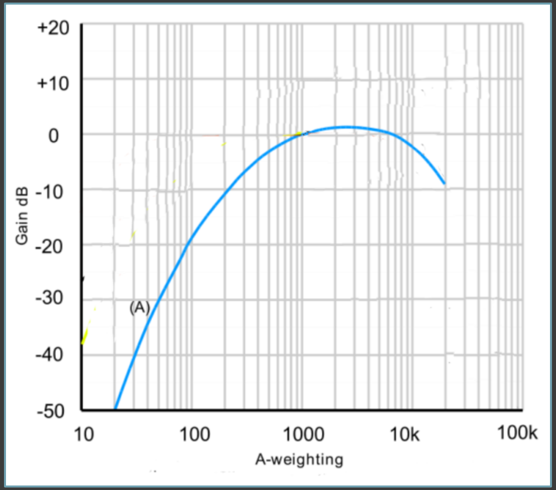


Source: http://en.wikipedia.org/wiki/Equal-loudness_contour

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

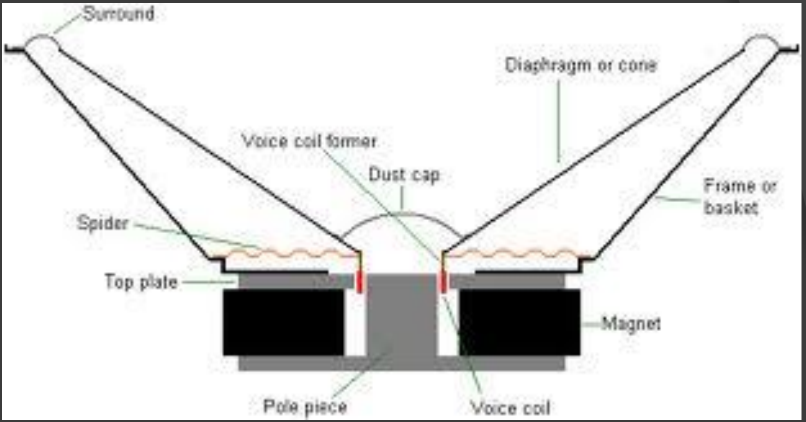
Source:http://en.wikipedia.org/wiki/Sound_pressure_level#Sound_pressure_level

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 (xmax, efficiency, distortion characteristics)
- Size of magnetic gap, length of voice coil (xmax, 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 while managing cost

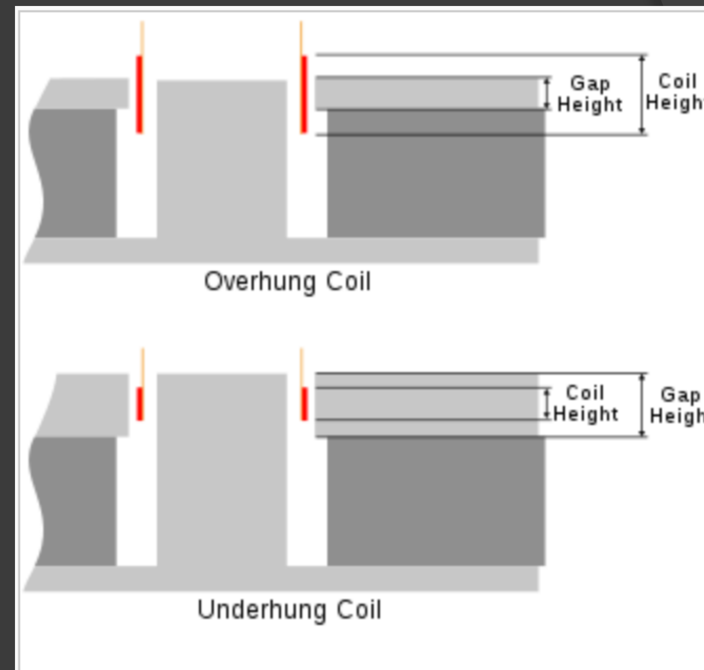
Driver efficiency

- Super efficient speakers can provide efficiencies as high as 4%, corresponding to an SPL of +98 dB at 1 watt at 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 (Xmax), providing higher volume and less distortion at low frequencies.

Source: http://www.hornlautsprecher.net/Dokumente/Grundlagen/Tiele-Smal-LSPRMTRS604.htm

Overhung vs. Underhung Voice coils

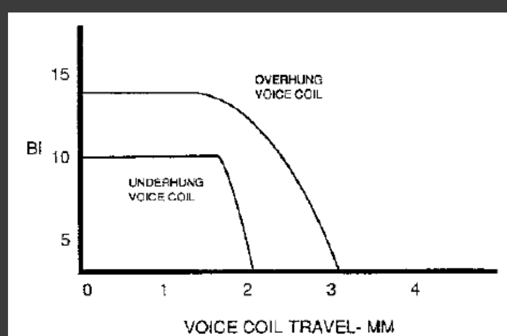
- **Overhung coil (most common)**
  - Used in the majority of drivers
  - Coil height is greater than the gap's height.
  - Higher coil mass than underhung
  - Soft non-linearity as the coil exceeds limits.
- **Underhung coil**
  - Used in high-end drivers
  - Gap's height is greater than the coil's height.
  - Lower coil mass than overhung
  - Hard non-linearity as the coil exceeds limits.



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

Source: Loudspeaker design cookbook



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

So what driver(s) to use?

- Must include the range ~ 100Hz to 7 KHz for high fidelity voice. This range covers “Hi-Fi” AM as well as CW, SSB, ESSB, FM
- 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 X 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.
- Thiele-Small parameters work well for small signals but are less accurate at high volumes or due to manufacturing variations. They are only uyseful at low frequencies, not applicable to high frequency analysis.

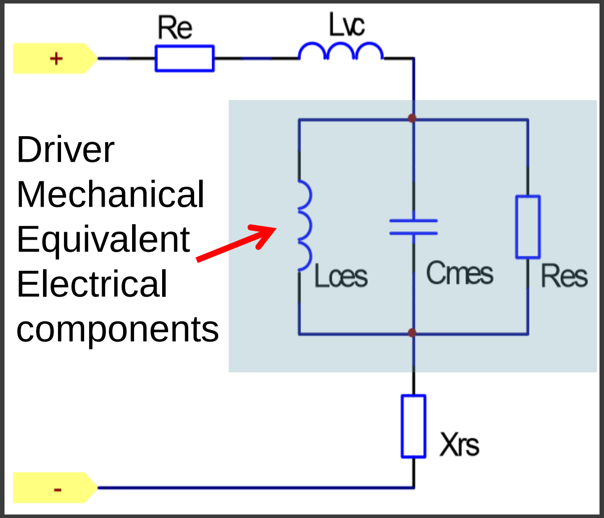
f_S, Q_E, Q_M, and V_{AS} along with V_B , the volume of the box, dictate the smoothness and shape of low frequency response that is obtained from a loudspeaker driver/box combination

So what happens at high frequencies?

- Upper frequency limit a function of radius of the radiating surface.
- Smaller radiating surfaces can reproduce higher frequencies than larger radiating surfaces.
- Cones exhibit radial and concentric resonances, radial being the most important. (Concentric is like the waves one sees when dropping a pebble in water)
- At some frequency the effective radiating mass of the cone becomes small and high frequency rolloff occurs.
- To achieve high cutoff frequency the ratio of voice coil mass and cone mass must be as small as possible.
- Upper frequency rolloff is also controlled by voice coil inductance. This can sometimes be a good thing if one wants to deliberately roll off high frequencies

Speakers Drivers for amateur radio can work well in the 3-5 inch diameter range for good reproduction of low to high voice frequencies depending on their specifications

Simplified Driver Model



Re = D.C. resistance of voice coil
Lvc = inductance of voice coil

Lces = suspension compliance equivalent inductance
Cmes = cone mass equivalent capacitance
Res = suspension losses equivalent resistance

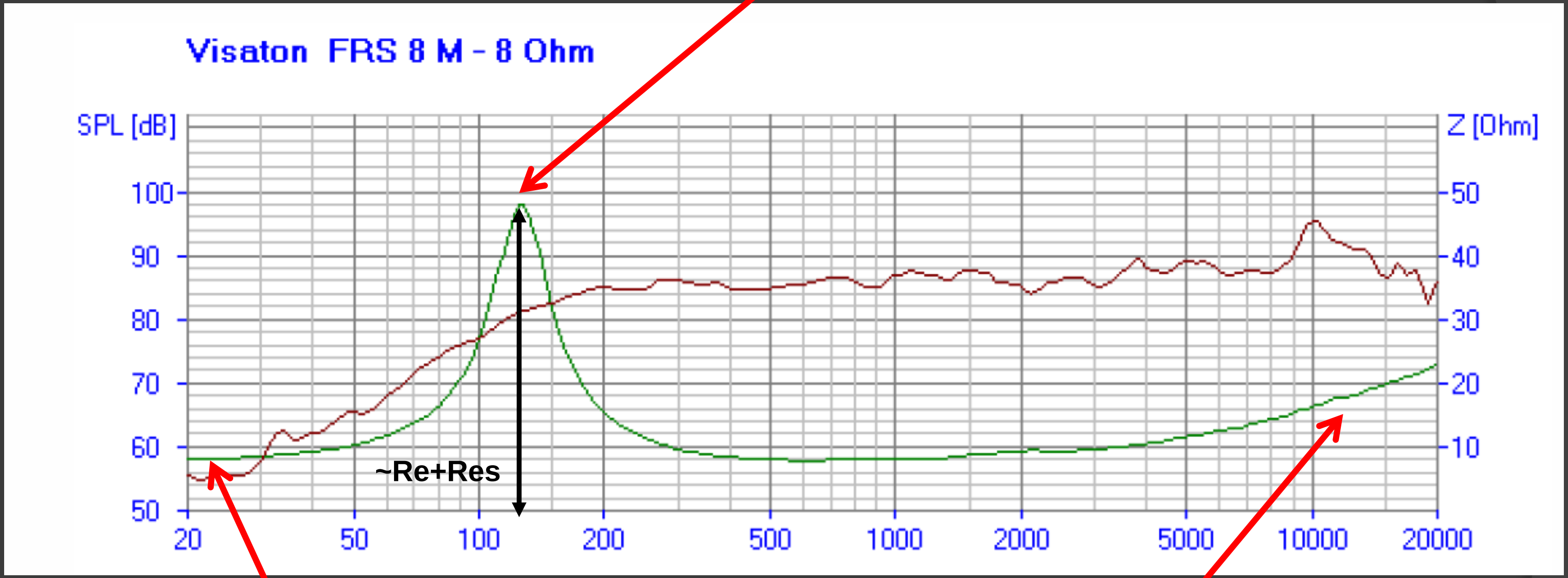
Xrs = radiation impedance representing voltage drop resulting from sound output

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

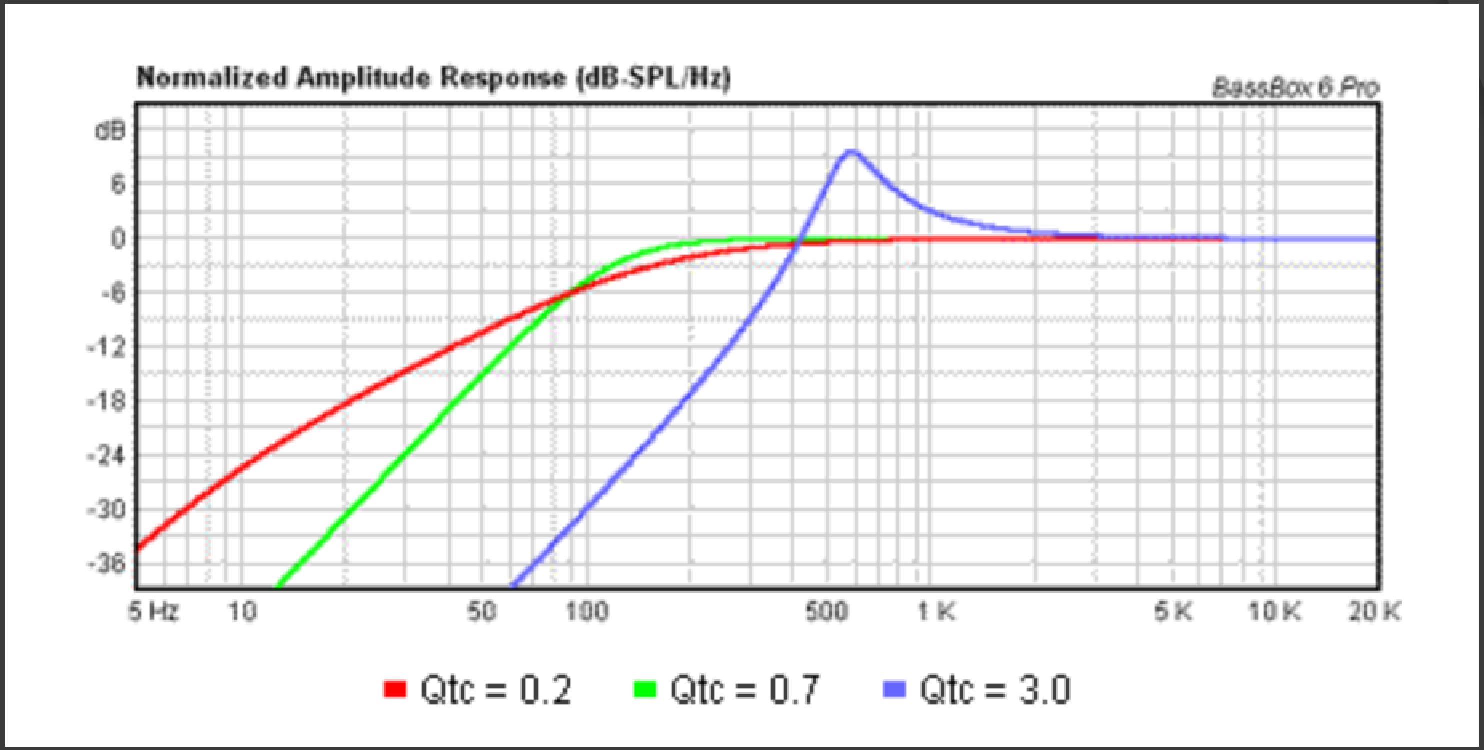
Impedance peak is a function of Qms.
In this example, impedance at resonance ~ 48 ohms



D.C. resistance (Re) = 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

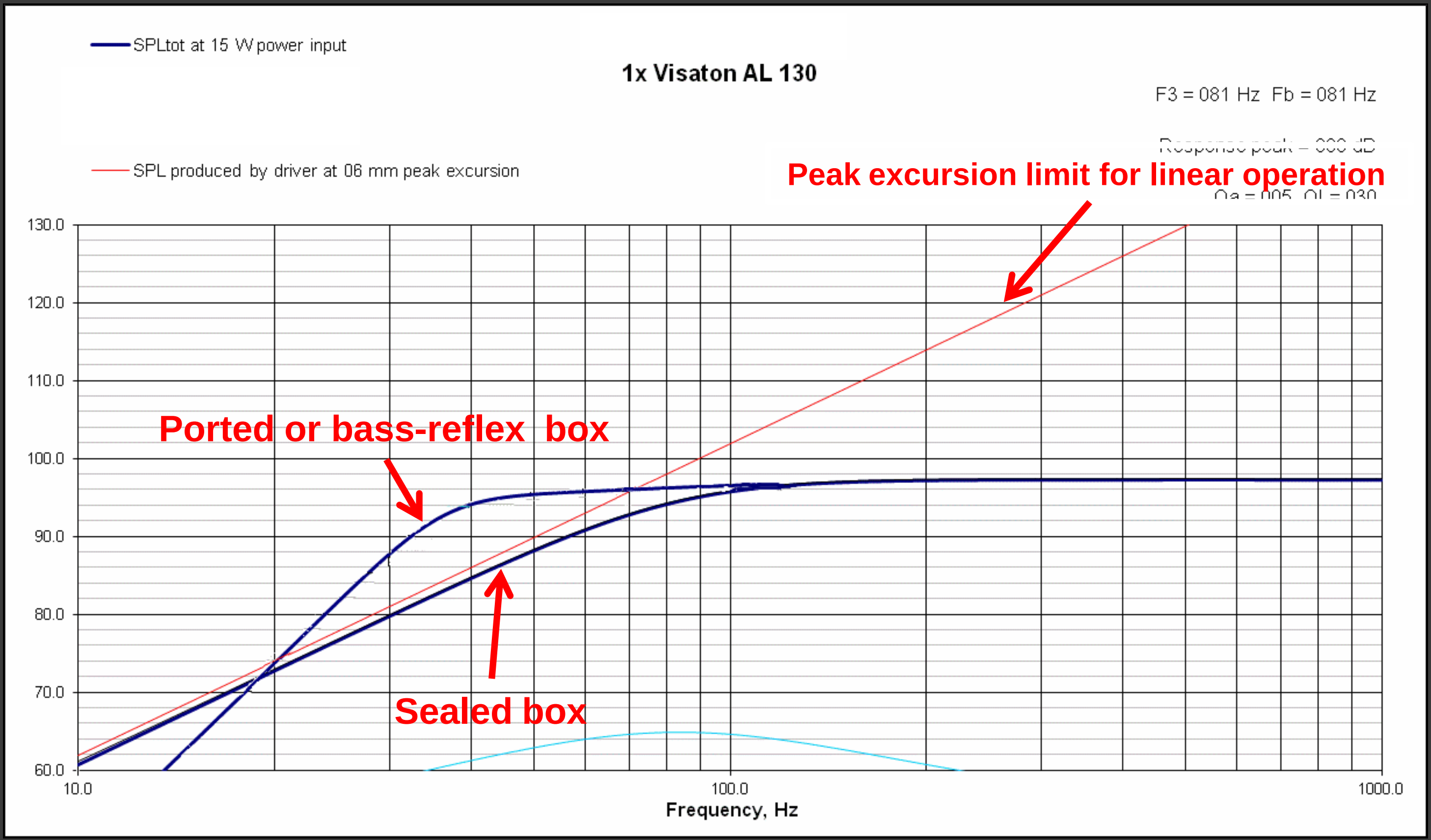
Effect of Qtc on low frequency response



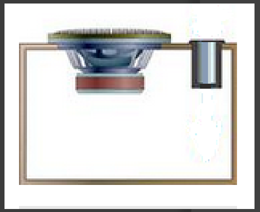
- **Qtc=.707: response is "maximally flat", meaning that the response stays level for as long as it can before dropping off**
- Qtc = 0.2: Box is much too large. Extends low frequency response but drops off sooner
- Qtc = 3: Box much too small – have large 6dB response peak causing coloration at the resonant peak and low frequency response drops off much too soon.
- Can use active compensation in an amplifier chain with a Linkwitz transform circuit.

Source: http://www.ht-audio.com/pages/SpeakerBasics.html

Sealed box vs. Ported box response



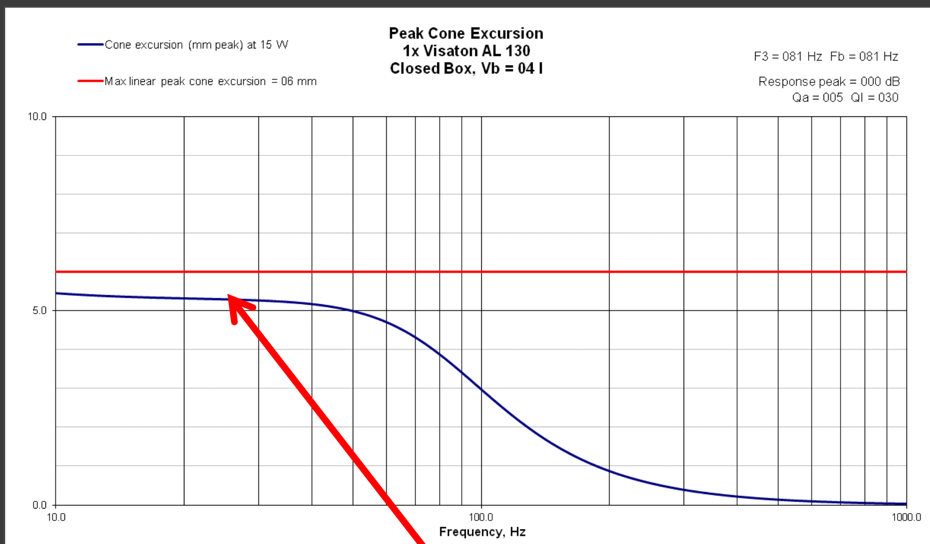
Sealed box

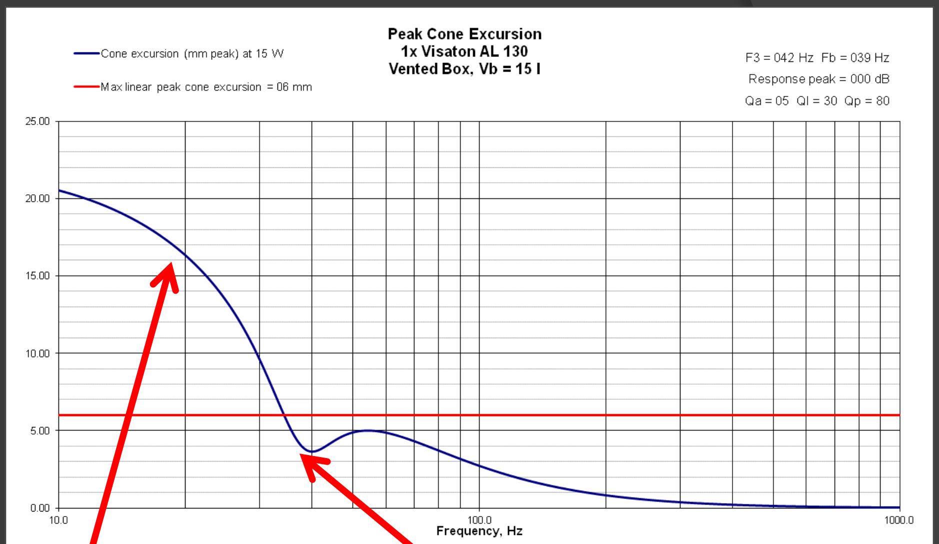


Ported box

- 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



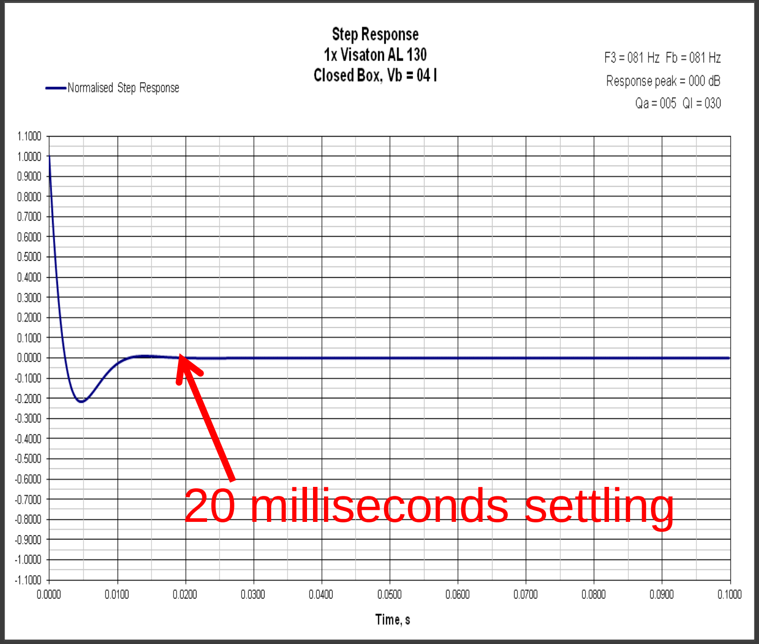


Excursion well-controlled at low frequencies. Air in sealed box acts as a spring and constrains speaker excursion. Typically no special filters required.

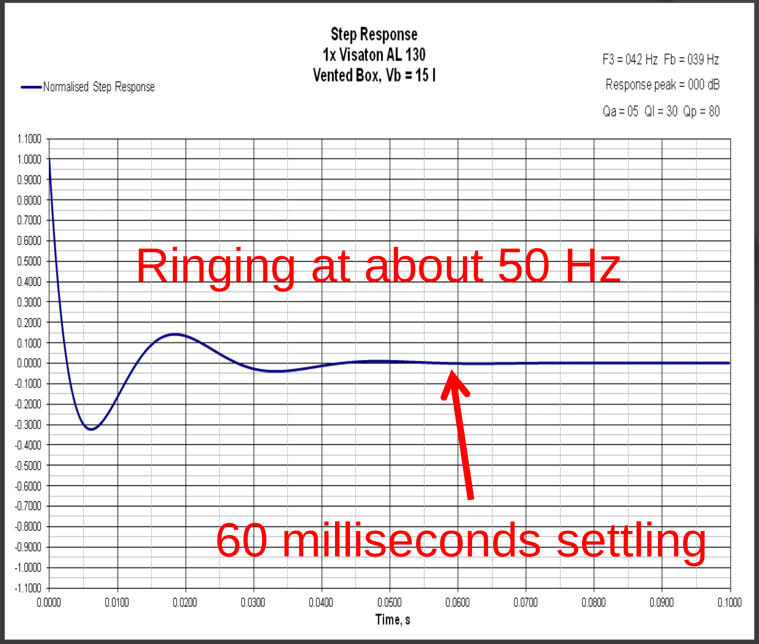
Excursion dip at port tuned frequency

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 can't be good for 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

Recommendation: Use of acoustic damping material is almost always beneficial

Photos courtesy Parts Express

Representative transceiver audio output specifications

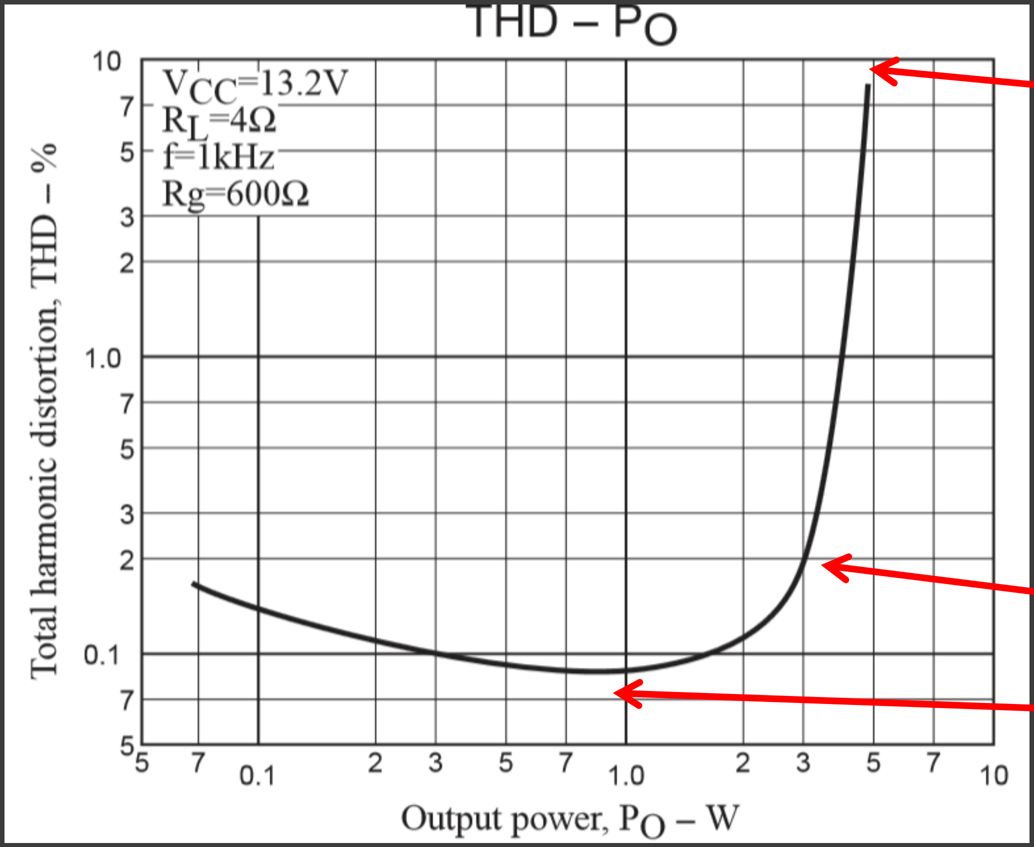
Transceiver	Power Output	Total Harmonic distortion	load
Elecraft K3	2.5W per channel	Typical 10%	4 ohm
Yaesu FT950	2.5W	10% into 4 ohm	4 -8 ohm
Icom IC756 Pro 3	2W minimum	10%	8 ohm
Icom IC7200	2W minimum	10% into 8 ohm	4-8 ohm
Tentec Eagle	2W into 4 ohm	<3%	4 ohm
Kenwood TS590S	More than 1.5W	10%	8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



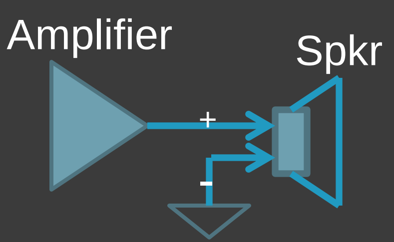
10% distortion at 5W

<0.2% distortion below 3W

Sweet spot at 1W out:
<0.1% distortion

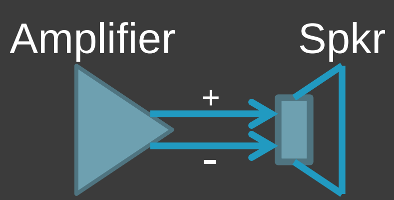
Distortion rises rapidly above ~ 3 watts with 4 ohm speaker, 1.5 watts with 8 ohm speaker

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) X (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.



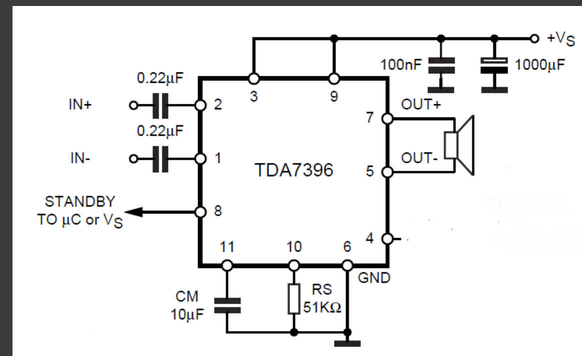
Bridge-Tied Load (BTL) Amplifier

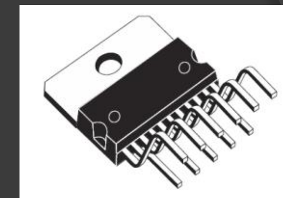
For a 13.8V power supply, let's assume each amplifier output can swing from 0.9V to 12.9V to stay in its linear region. The two outputs swing in opposite directions. That's 24 volts peak to peak or 12V peak. For an 8 ohm speaker, Maximum power out = 12*12/16 = ***9 watts***. For a 4 ohm speaker, that's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

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

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





- 2x8W at 4 Ohm TPA3110 Class-D Audio Amplifier Board $9.98 Parts Express # 320-329 and use one channel. Requires external pot

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 when on sale

Class AB amplifier recommended for no EMI.

Build your own small, good performing, 4 ohm sealed box speaker for about $33.24 plus ~ $10.00 cabinet wood or mdf + glue!

Item	Qty	Vendor	Descriprion	Distributor	Distributor P/N	Unit cost	Total cost
1	2	Fountek	Fountek FE83 3" Full Range Driver 8 Ohm	www.parts-express.com	299-020	6.90	$17.83
2	1	Sonic Barrier	1/2 inch self sticking acoustic foam	www.parts-express.com	260-520	$9.97	$9.97
3	1	Parts Express	round speaker terminal cup spring type	www.parts-express.com	260-294	$1.25	$1.25
4	1	Switchcraft	Switchcraft MDSL2A mono phone jack 3.5mm	www.mouser.com	502-MDSL2A	$2.51	$2.51
5	4	parts express	rubber cabinet feet .88" X.31"H	www.parts-express.com	260-7706	$0.42	$1.68
						Total	**33.24**

Note: Shipping costs and cost of cabinet MDF or plywood + misc hardware not shown. Required closed box volume 0.12 ft^3 or 3.4 liters.
Use Speaker box volume calculator/designer for box dimensions and calculations

- Impedance: 4 ohms (wire two 8 ohm drivers in parallel in phase)
  SPL: 87.2dB (simulated in UniBox) – fairly efficient with good headroom
- 3db lower cutoff frequency: 144 Hz (simulated in UniBox),
- frequency response 100Hz-25KHz

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

Example of a good commercial speaker for amateur radio use

Avantone Passive MixCube Monitors In Black

Used in the music industry for
Mixing for typical auto speaker sound

SPL / Sensitivity
93dB @ 1w / 1 meter

Cabinet
sealed / 18mm MDF / Dacron acoustical stuffing

Frequency Response 90Hz - 17,000Hz

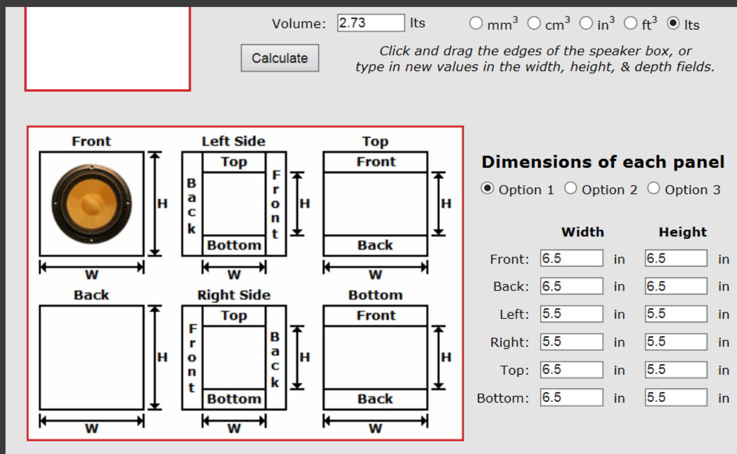
Impedance: 8 ohms

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

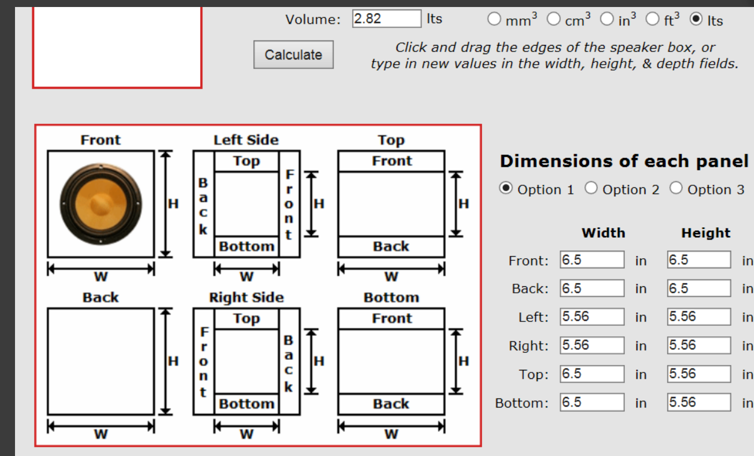
Driver
5.25" cast aluminum frame

~ $149.00

Or build your own high efficiency 8 ohm speaker <$43 with an MDF or plywood cabinet



½ inch MDF cabinet



½ 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	2.90
6	1/2" X 2 ft X 4 FT MDF panel	Home Depot	1508108	1	8.89	8.89
					Total	42.67

Plus wood glue, Silicone sealant, Finishing matl's

SPL 90dB 1W/1M, 90-15K frequency response, f_{3db} = 144Hz simulated in UniBox, Qtc = 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 ½ inch or 3/4 inch MDF for its density and low resonances. Plywood also OK
- Use a single full range driver with high efficiency (>85dB 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 > 7KHz.
- 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 <u>4X</u> 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. Choose cloth or rubber surrounds.
- Be creative in finding ready-made speaker cabinets if you don't want to build your own

Representative homebrew speakers

Hammond metal case ~ $20
-Nice black finish
-Good sealing
-EMI shielded
-Difficult to drill large circular hole in front panel
-Requires internal amplifier

Packaged in plastic electrical box. Inexpensive with good sealing. Can paint and saw off tabs

Made from old solid wood speaker cabinet. New removable front panel

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 Thieie/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 volume designer/calculator: http://www.diyaudioandvideo.com/Calculator/Volume/
- 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