Low bass accounts for 30% of listener satisfaction.
- Sean Olive

Subwoofer Camp

deep bass & reduced main-speaker distortion
for high-fidelity enthusiasts & audio professionals

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One subwoofer "camp" believes in traditional *full-range-in-a-box* loudspeakers. However locating *main* speakers in a home listening or studio control room, resonant echoes create *over-loud peaks & silent valleys, uneven note-by-note,* and *differing at each listener location*. Perceptions at home of mixing decisions may well disagree.

The other camp *redirects* low bass to one or more subwoofers (SW), positioned for mildest boost\canceling. Relieving main speakers of low bass they can't handle as well lowers their *harmonic (HD), intermodulation (IMD), & multi-tone (MTD) distortion*. So subwoofers improve main speakers' reproduction well into mid & high frequencies.

This brief explores: 1) what produces very low frequencies (VLF); 2) The importance of reproducing VLF; 3) That using subwoofers solves VLF acoustic issues for full range audio reproduction systems; 4) That subwoofers reduce several forms of unintended distortions across the full audio range; 5) That using subwoofers contributes to more accurate monitoring in the studio, and greater enjoyment of audio content at home.

Sources and acoustics that produce low bass

Pop music instruments that produce VLF are electric bass (41Hz) & kick drum (60). More demanding in VLF are acoustic orchestral bass drum (~35Hz), double bass viols (32.7), tuba (29), contrabassoon (29), piano (27.5), organ (16), & movie effects (20Hz). Large concert halls & studios reinforce VLF sounds, calling for capable VLF playback. VLF-deficient *loudspeaker-in-room* systems deny listeners the thrill of lifelike bass.[1]

San Diego Symphony's 100 members under Rafael Payare perform at Lehigh University in Bethlehem PA the evening before its debut at Carnegie Hall in New York City 2023. Live & recorded spectra are overleaf.

[1] With weak or no VLF, we perceive only *phantom* fundamentals by their harmonics, original or distortion, cf. FN5.

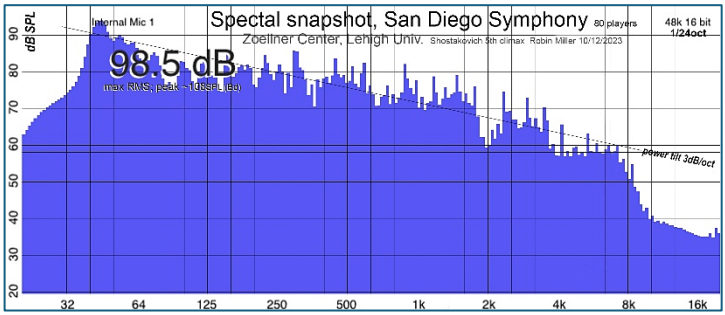


Fig.1 - Live real-time analysis (RTA) midway back in a 1003-seat hall shows a natural "tilt" of 1~3dB per octave. Of human hearing's audible 10 octaves 20~20kHz, we task subwoofer(s) with the most difficult lowest 2~3 octaves, where floor-standing 'tower' speakers are less capable of low distortion.

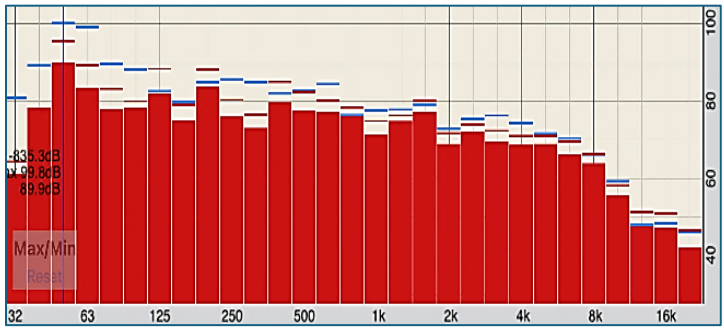


Fig.2 - Playback RTA over studio monitor-quality speakers including stereo SWs shows lifelike 100SPL peak lines above average bars. Tilt is due to powerful low bass instruments + room support, preserved comparable with the spectrum heard live, and desired on replay. Sound above 8kHz may fall sharply.

A subwoofer (or two?) and Bass Management *for best audio content reproduction*

That "bass accounts for 30% of listener enjoyment" is true at a live concert. Also at home with a subwoofer, whether in stereo or surround, or even with the *panned-mono mics* of popular music. Audio-video receivers (AVR) with DSP, setting main speakers to "small," properly filter all speakers' signals, but low bass is monophonic no matter how many SWs are paralleled. (Later we explore even more lifelike *stereo bass*.)

Main speakers – 'bookshelf' or floor-standing 'towers' – can be over-burdened with VLF in 2~3 octaves of our hearing's 10 octave range. 'Mains' speakers struggling with VLF generate bogus harmonics, buzzing *multi-tone* artifacts, and the 'semi-clipping' of *level compression* when cone motion cannot accurately follow the audio signal. "Active" SWs usually do *not* high-pass filter (HPF) audio signals passed on to main speakers to spare them generating distortion throughout their range (details soon).

A subwoofer's own distortion is *post-crossover,* so is *not filtered* by it. The extent a SW distorts is determined by its quality (cost?), and by playing it at too high a sound pressure level (SPL).[2] SW distortion artifacts reach well above crossover where it is *localizable*, smearing the *soundstage, masking* mains speaker sounds, and adding to main speakers' *harmonic (HD), intermodulation (IMD), & multi-tone (MTD)* distortions. Each issue is dealt with here, based on the well-accepted science of human hearing.

[2] dB *sound pressure level* (SPL) ranges from the "*threshold of hearing*" at 0dBSPL to a *painfully* loud 120dBSPL.

What* bass *we hear is* not *what the wattmeter says

The brain "transposes" sound (the *cause*) to *perceived* hearing (the *effect*). *Watts* measures the power from amplifier to loudspeaker, reproduced as acoustic Sound Pressure Level, in **dBSPL**. But we *hear* sound differently, in **dBPHON**. Fletcher-Munson 1930s *Equal-Loudness Contours* (updated in ISO:226) relate various sound power levels in dBSPL to perceived hearing in dBPHON. Their values are coincident at 1kHz. [3]

Fig.3 transposes Equal-Loudness Contours to *Equal-SPL Contours*, the *ear's* level-dependent *frequency response.* A *dynamic* recording's levels can span from **0** dBSPL *threshold* to **105** dBSPL, comparing well to the live concert in *Fig.1&2*. Played at lifelike level, *Loudness* above 500Hz generally spans the same total **105**dBPHON. However as frequency decreases below 500Hz (~C5), average hearers suffer worsening *deafness,* at 20Hz reduced to a perceived total dynamic range of only **55**dBPHON (from 50~105).

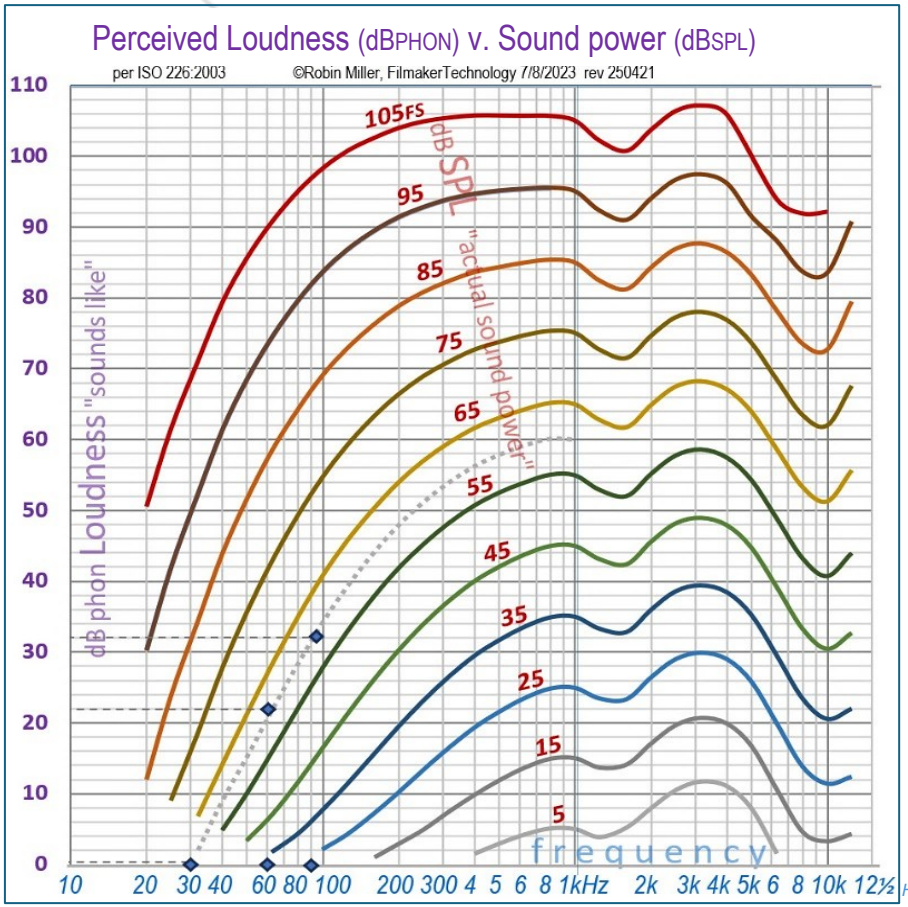


Fig.3 – Equal-SPL Contours (transposed Equal-Loudness Contours of ISO:226-updated Fletcher-Munson) show the average human "ear's frequency response." On the **60 dBSPL** curve - - -, a ***30Hz*** *fundamental* is inaudible at **0PHON** (lower left ◆). However a **60Hz** 2nd distortion harmonic is *audible 28dB softer* at **32 dBSPL**, a **90Hz** 3rd harmonic has been *audible since 38 dB softer,* at **22 dBSPL.**

[3] For clarity, values are color-coded as **frequency**, actual physical **dBSPL**, & perceived loudness in **dBPHON**.

Below 500Hz along steepening diverging Contours,[4] *fewer & fewer dB change in SPL* cause *greater change in dBPHONS*. Points ◆ in ***Fig.3*** show a 30Hz fundamental is too soft to hear until it reaches **60dBSPL**. On the **60SPL** curve ▪ ▪ ▪ cf. **105**, a *change* of only **45**dBSPL causes a **69**dBPHON change, from **0** to the **69dBPHON** intercept with 105dBSPL. Above 500Hz, a change in SPL higher by ~+10dB *doubles* perceived loudness; lower by –10dB *halves* it. But at 30Hz, only a –5dBSPL change sounds *half* as loud. A speaker's specified "frequency range" implies a drop of –10dBSPL that sounds *a quarter* as loud*!*

VLF "inflated harmonic distortion" and other distortions alter tone color (timbre)

THD can be audible even if we can't hear its fundamental ancestor*!* [5] Think *musical diminuendo,* as tones slowly soften in SPL. The fundamental diminishes faster than its higher harmonics, fading but with increasing brightness (bogus tone color, timbre). *Total harmonic distortion* (THD) mimics a higher % than measured. In ***Fig.4***, a 60Hz tone's *THD measuring 3% can sound like 10%*. At 30Hz, *3% THD sounds like 25%!*

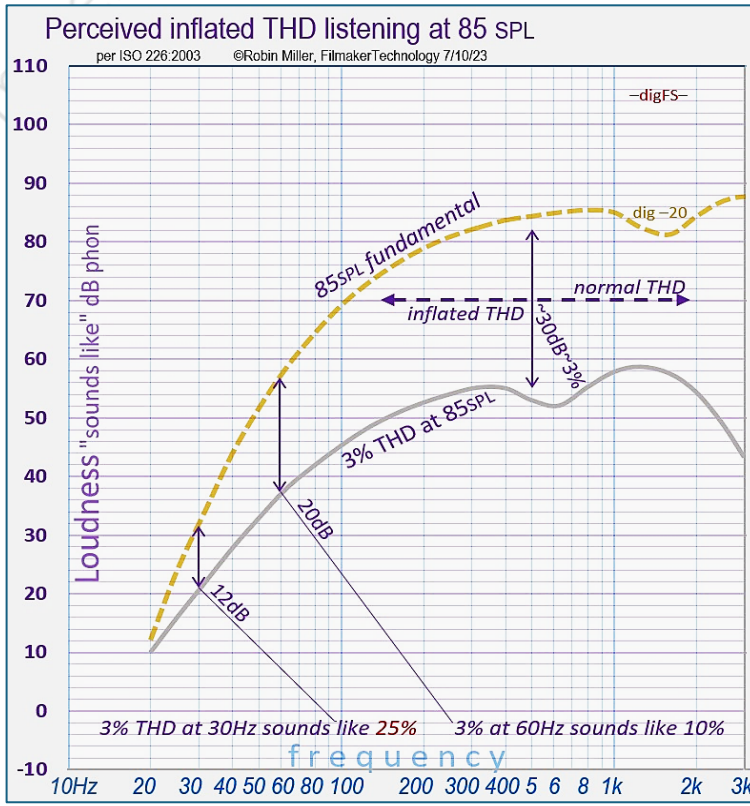


Fig.4 – (Derived from Fig.3.) Listening to fundamentals at lifelike **85SPL,** we perceive 2nd & 3rd distortion harmonics louder than a measured %THD implies. For a 60Hz fundamental, a measured 3% THD sounds like 10%. For 30Hz, 3% sounds like 25%. Driver distortion is mechanical, post crossover.

[4] "Diverging" Loudness between Contours at LF is apparent in *Fig.3* by counting vertical divisions every 2dB.

[5] Organ builders for centuries have played this trick to save the cost of up to 32ft and longer pipes. *Resultants* rely on listeners' *filling-in* a missing VLF fundamental, although only hearing its unique 2nd & 3rd harmonics from pipes ½ & ⅓ as long. It's also how we *think we hear* low bass from boom boxes & phones with tiny speakers*!*

Intermodulation Distortion (IMD) requires two tones, *even if one or both are too soft to be audible!* G1 at 49Hz and its 7th F2 at 87Hz create a difference tone of 38Hz and a 136Hz sum tone that we can direction-find, undesirably diverting attention to the SW. Beyond IMD*'s "burr"-sounds, m*usic's many tone-pair combinations generate *buzzing multi-tone distortion (MTD)*. Most *active SWs* don't high-pass filter (HPF) audio merely passed through to main speakers, overworking mains with VLF to cause MTD, in *Fig.5*.

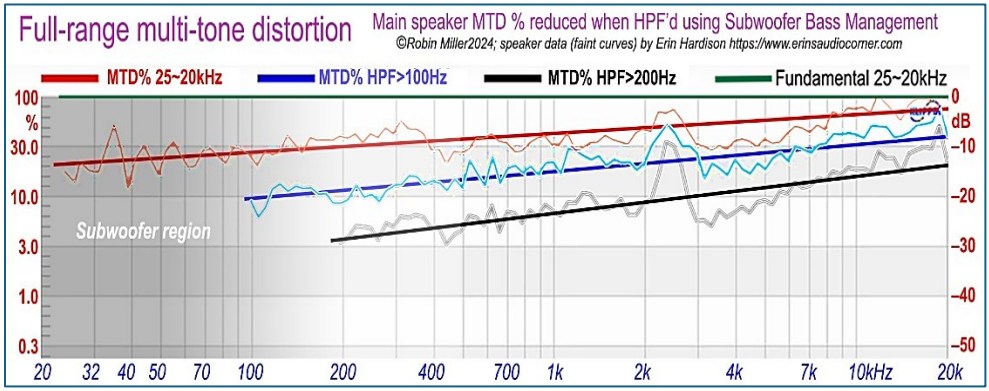


Fig.5 With no SW, VLF can cause main speakers to have buzzing multi-tone distortion (MTD) of ***30% in red***. Bass management that HPF-ers signals to main speakers at 100Hz can reduce MTD to ***~20%***, to **~7%** MTD when HPF'd above 200Hz. *Data Erin Hardison* https://youtube.com/watch?v=i1sa50hzEcM.

Listeners object to distorted classical, jazz, & movie acoustic music after having experienced it *live & undistorted*. Distortion matters less to those who have not heard the original, such as electric pop processed in a studio. Even played softer than live, distortion causes listener complaints of fatigue, and "The sound is too loud." Memory may forgive musical harmonic distortion, but not burr-sounding IMD or buzzing MTD.

A good subwoofer reproduces clean low bass AND cleaner main speaker sound

The topic of room acoustics could fill a library. Suffice to say absorptive treatment especially below ~300Hz is thick and expensive. Alternatively, placing subwoofer(s) where mains can't go effectively *position-EQ's* a room's VLF at more listeners' seats.

A SW's job is mostly to produce low bass sounds' fundamentals. Then the mains' higher frequency harmonics, heard alone, *direction-find* the sound. But we also in error direction-find a SW by its above-crossover distortion. Heard from two angles instead of one *tears* auditory events from main speakers, defocusing the *soundstage*.

Some audiophiles decry using a SW when it is heard to smear the "soundstage." Unaware it is directional distortion generated after the SW's low-pass filter (LPF), they have yet to experience clean low bass that cannot be direction-found. Not filtered are the SW's distortion harmonics & IMD\MTD sums far up-spectrum and easily localized. Integrating a SW requires a low-distortion one having inaudible localizable artifacts.

Again, active SWs that do *not* high-pass-filter (HPF) signals wired to pass on to main speakers cause them to distort. Bass management, in DSP in an AVR setting mains to "small" or in a stand-alone analog unit, reduces mains' distortion full-range, in *Fig.5*. Along with level compression, mains distortion can *mask* its own higher pitch sounds.

Masking is a loud tone concealing softer usually higher pitch tone within a *critical band*. Always loud pop music spawns lots of masking; less with dynamically sparser acoustic music. SW distortion above crossover can also mask main speaker sounds. But masking in the SW's single critical band does not occur when the *masker* is only distortion inaudible below ~70SPL,[6] as in *Fig.7L*. Nor with fleeting sounds, e.g. LFEs. All told, savvy enthusiasts use low distortion SWs, and HPF signals to main speakers.

Perceived bass Loudness is affected by playback volume

Many recording, mixing, mastering, & motion picture studios respect a monitoring level standard of 85dBSPL. This maximum *average* reference coincides with the OSHA exposure to workplace noise over an 8-hr shift. Lifelike audio needs *headroom* of up to 20dB for dynamics peaking at 105dBSPL per channel *full scale* (FS). Naturalness is lost with abusive level-compression in broadcasting and popular music. Explosions in the sparsely used 0.1 LFE (enhancements) channel add 10dB more to peak levels.

Consumers find relief from listening fatigue due to level compression & distortion by playing softer than the standard, at ~75dBSPL. But, per Fletcher-Munson (ISO:226), listening at 75dBSPL weakens bass. *Fig.6* illustrates how playing an 85dBSPL recording at 75dBSPL needs a broad 6dB boost at 40Hz to hear bass as balanced by musicians and producers. Softer than 85dBSPL by 20, 30, or 40dB as background music needs a boost of 10~13dB. Or louder than 85dBSPL, attenuate 8~19dB, unless addicted to it! [7]

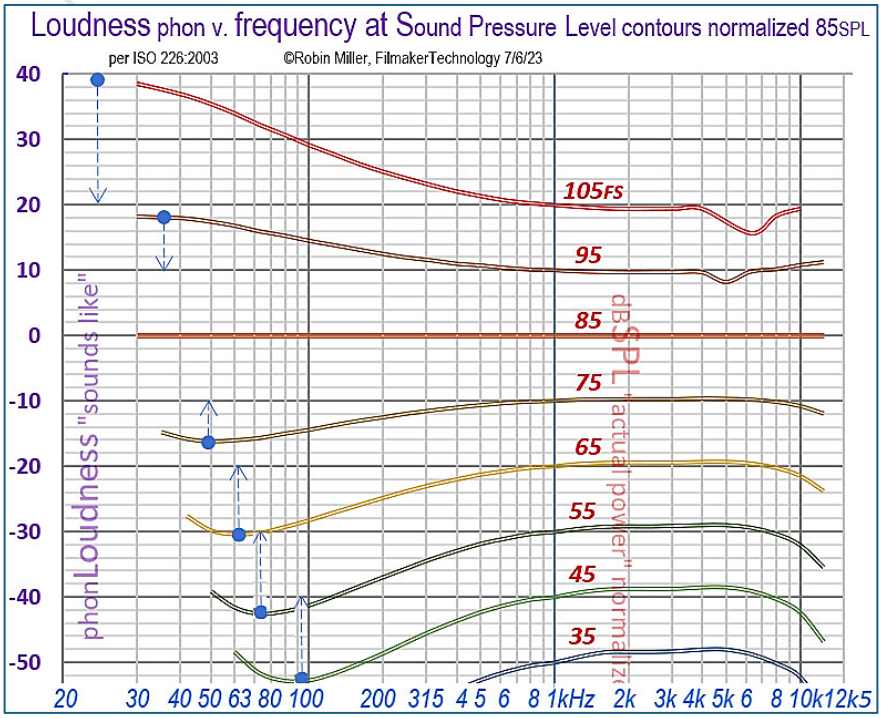


Fig.6 – Listening at SPL different from the equalizations baked into a recording at standard 85dfBSPL by its producers.

[6] L. Fielder & E. Benjamin "Subwoofer performance…" 1987; F. Toole "Sound reproduction…" 3rd ed. p96.

[7] Early audio controllers featured Loudness compensation for a balanced spectrum at lower listening levels.

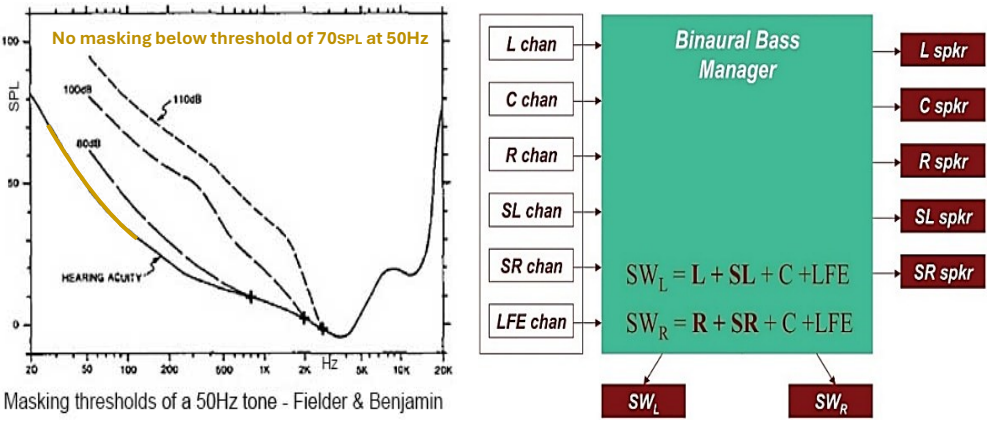


Fig.7 – L: Fielder & Benjamin found no masking of main speakers by a low distortion SW up to 70SPL. ***R:*** a stereo bass manager (SBM, aka BBM) redirects VLF in 2.0 stereo to 5.1 via low pass filters (LPF) to two (four?) SWs along side walls. Unlike most active SWs, the SBM high pass filters (HPF) main channels to integrate ("splice") with mains to reduce mains' THD, IMD, & multi-tone distortion (MTD).

Spatially lifelike stereo low bass *at home or mixing studio*

Thrilling lifelike bass awaits in most digital recordings found to contain *stereo bass,* demonstrated by the author perceivable to 45Hz between side hemispheres [R. Miller 2005 [8]]. It is captured by a microphone at the *critical radius* of a reverberant hall, where the energy sum of *reflected* sounds equals the energy of the *direct sounds* that traveling line-of-sight from instruments & voices. Farther in the hall, the live audience hears even more unseen *indirect energy* than *direct*, and even more stereo low bass.

Enroute at the speed of sound, room reflections travel along different paths, each with its own "flight-time." Reverberant acoustics cause each instrument's sounds to arrive at each ear or microphone at differing times. Performed with vibrato (frequency modulation), each sonic arrival also differs in frequency, though originating from one source. Acoustic instruments that with vibrato produce *binaural very low frequency (VLF)* include bass viols, tuba, bassoons, bass drum, organ, contra-anything. Or the Doppler Effect vibrato of a spinning Leslie & Hammond B-3 in a large recording studio.

Say a bass or Leslie plays vibrato at 90Hz shimmering with 91Hz. The 90Hz version arrives at an ear or mic after reflection from a side wall at the same instant as 91Hz arrives directly. One instrument heard as two, then three from another reflection, etc. Or at ¼ of an orchestra's total power, a 40in (1m) bass drum's *batter head attacks* when smacked at 32Hz, then its *resonant head* glissandos up to 34Hz. The profusion of these sonic events arriving simultaneously at each listener's ear or mic channel renders each source as a *chorus of itself*. Heard live, the VLF arrivals differ between the L & R hemispheres, creating *binaural differences* – stereo bass. Artificial reverb seeks to simulate this effect. Many instruments multiply all the individual choruses. Of all musical content, acoustic chorusing is thrilling in a concert hall live, or…

[8] "Physiological and content considerations for a 2nd LF channel…" AES, ASA, CAA, VDT demo & 2005 paper at www.filmaker.com. Most movie and acoustic music recordings are found to contain stereo bass that is lifelike in spatiality, but often not in popular music when electric bass guitar and kick drum are panned to center (mono).

... or recorded. Using passive SWs along L & R side walls, an analog stereo bass manager (SBM) is inserted between control\preamp & power amplifiers, as in *Fig.7R*. Sadly no new consumer SBMs survive (e.g. Outlaw Audio ICBM) and few professional (StudioComm Mod. 65); the author knows no AVR implementing stereo bass in DSP.

A simple DIY method provides BOTH stereo bass management AND high pass filters signals to main speakers. It works with active mains and two active subwoofers along side walls. Feed Left (& Surround Left) preamp\controller unbalanced line outputs to the left SW's L & R unbalanced line inputs, Right (& Surround Right) to the right SW. [9] Then to HPF signals passed to two main speakers (or four of five mains counting on less VLF in the Center channel signal), insert a low distortion film capacitor "C_{in}" determined by the main's input impedance "R_{in}" and the desired crossover frequency "f_{in}." [10]

Takeaways from "Subwoofer Camp"

Subwoofers should be *heard but not seen*. But subwoofers *can be 'seen'* (localized) by their audible distortion. *Unseen* are the *silenced sounds* of main speakers masked by their own and SW distortion. And as shown in *Fig.5*, without Bass Management HPF-ing signals to main speakers causes mains *semi-clipping compression* and MTD.

Lifelike sound requires linearity. Loudspeakers, excited simultaneously with myriad tones across the full range of sound power levels (SPL), generate more distortion than any other link in the audio chain, from mics to ears. Consumer SW makers strive for less than 3% THD; professional models less than 1%, plus IMD & MTD. SW distortion is mechanical, post crossover electronics, so distortion artifacts are not filtered by it. For best sound, do not push a SW to overload, and share the load with two (four?).

A lone subwoofer channel, mono regardless of how many SWs are paralleled, loses the stereo low bass in most recorded music & movies.[11] Stereo Bass Management (SBM) preserves *envelopment* of binaural VLF between the ears' L & R hemispheres.

While some prefer the "brighter" sound resulting from distortion, especially benign 2nd harmonic, distortion is anathema for listeners whose reference is remembered live tonality. As in ***Fig.4***, distortion is "inflated" as low frequency fundamentals fade but higher distortion frequencies take on a higher effective percentage. Unaware of this knowledge, music enthusiasts may not be enjoying the thrill of clean lifelike sound.

The author has enjoyed many years recording & mixing music to dramatic features, and as a studio, cinema, and home theater engineer who shares expertise with clients and readers of his publications at www.filmaker.com. Reputable loudspeaker makers devote considerable resources to reducing distortion. Are they foolish for doing so?

———————

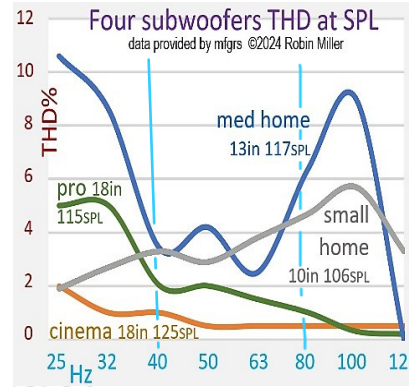
[9] Active SWs' L & R speaker or line level inputs are mixed internally to mono, but not the passed-thru signals.

[10] For f_{in} of 80Hz and R_{in} of 10kΩ, C_{in} is 0.2μF. For other values, calculate $C_{in} = 1 / (2\pi f_{in} R_{in})$. Or buy 1 or 2 pairs of Harrison Labs' FMOD inline RCA 12dB/oct high pass filters by choice of frequency (at Parts Express).

[11] To position a single mono SW in a room: place it temporarily in the owner's seat (sweet-spot) playing bass-rich music, then "crawling" the walls, listen for the most even sound. When found, place the SW in that spot.

Appendix – not an ephemeral shoppers' guide, but a reference for subwoofers at four price points

For the technically-minded, "a picture (graph) is worth a thousand words." Frequency decreases to left; SPL and % harmonic distortion rise on vertical axes.[12] This paper advocates for low distortion along with smooth frequency response: both are "pictured" in these examples. ***Fig.8***→ compares all four examples, showing THD by application. VLF are in 3 octaves 16~125Hz. All but the "small home 10in" are shown at high SPL for fleeting peaks & LFE; at average level THD is lower. *Spinorama* (*CTA\CEA 2034)* reviews by Audio Science Review or Erin's Audio Corner mostly cover main stereo or surround speakers, but both recommend subwoofers for reasons given in this paper.



Low-priced active 10in SW 95SPL for small home stereo or THX-certified home theater
*(**THD <5%** at 110SPL PORTED, 100SPL SEALED 22~80Hz; **THD <3%** at 95SPL ¼-space, est'd)*

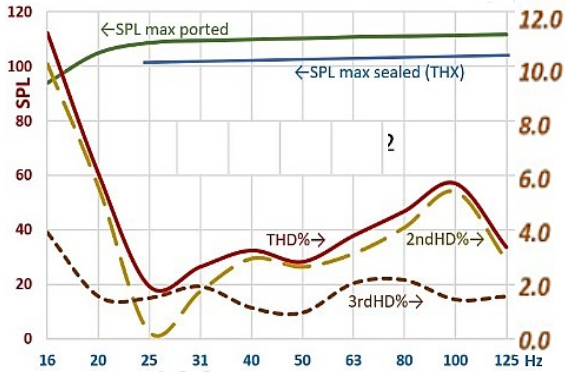
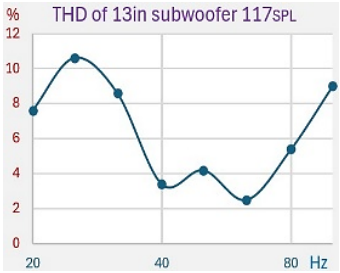


Fig.9 - From manufacturer's data, a budget SW well-controlled at 2% of objectionable 3rd harmonic distortion down to <20Hz, less objectionable 2nd HD dominates 4% 22~80Hz, both at 110dBSPL ported, or 100 sealed.

Mid-priced active 13in SW 105SPL for medium home stereo or THX-certified home theater
*(**THD 3~11%** at max 117SPL 20~100Hz ported\sealed; **THD <3%** at 105SPL ¼-space, est'd)*



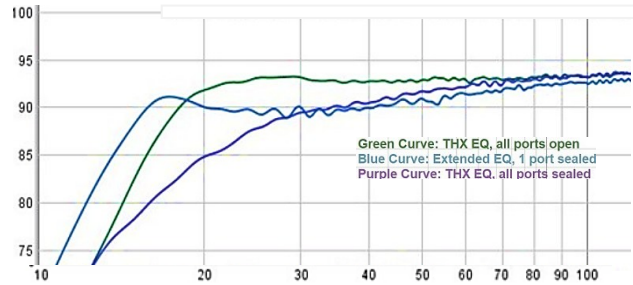


Fig.10-L: Depicted on p1, this long-excursion optimized SW (data not from manufacturer) is likely <3% THD at 105SPL, far preferable to the "20%" some claim is acceptable. ***R:*** Responses ported (higher SPL at 20Hz) or sealed (rings less). Sealed response can be flat -3dB at 35Hz with a broad EQ boost of 3dB (double power). Data courtesy James Larson - www.audioholics.com/subwoofer-reviews/monolith-13201d-thx-ultra .

[12] 105SPL is digital full scale 20dB above standard 85SPL, or home listening at 75SPL with LFE peaks at +10dB.

Mid-priced passive 18in SW max 130SPL for large home cinema, professional music PA system
*(**THD <2.5%** at 115SPL ≥35Hz ½-space outside; **<0.5%** at 105SPL ¼-space inside, est'd)*

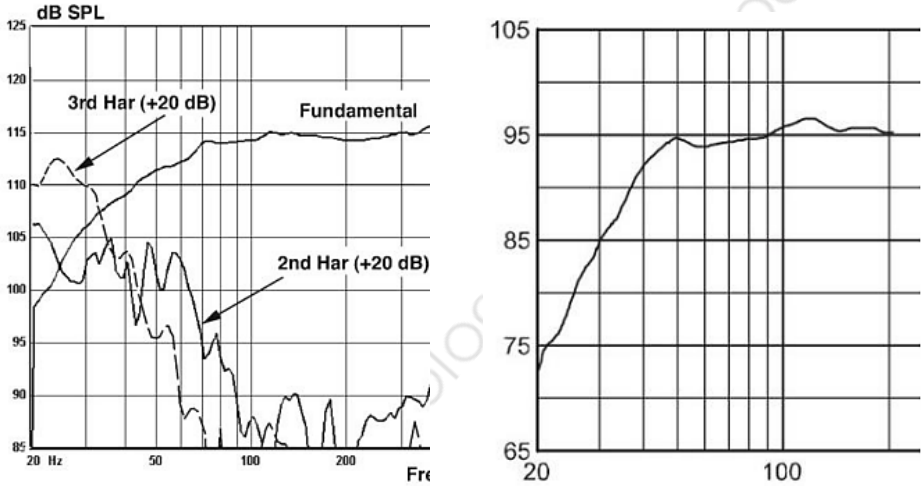


Fig.11-L: Even at 115SPL for PA, this driver "bare" at 70Hz exhibits 1% of the more musical 2nd harmonic, 0.3% of the less musical 3rd harmonic (raised 20dB, the distortion % is 1/10 of the -20 & -30dB ratios shown). Inside level distortion drops greatly to <0.5% at 35Hz. ***R:*** Factoring in that fundamentals only are boosted by a ported enclosure, response is flat -3dB at 40Hz with no EQ, flat to 30Hz with mild 3dB EQ. [Data: JBL 2268.]

High-priced passive 18in SW max 140SPL for THX-certified cinema, mixing stage, largest home cinema
*(with enclosure in ½-space **THD <1.5%** at 116SPL ≥29Hz; **<0.3%** at 105SPL ¼-space, est'd)*

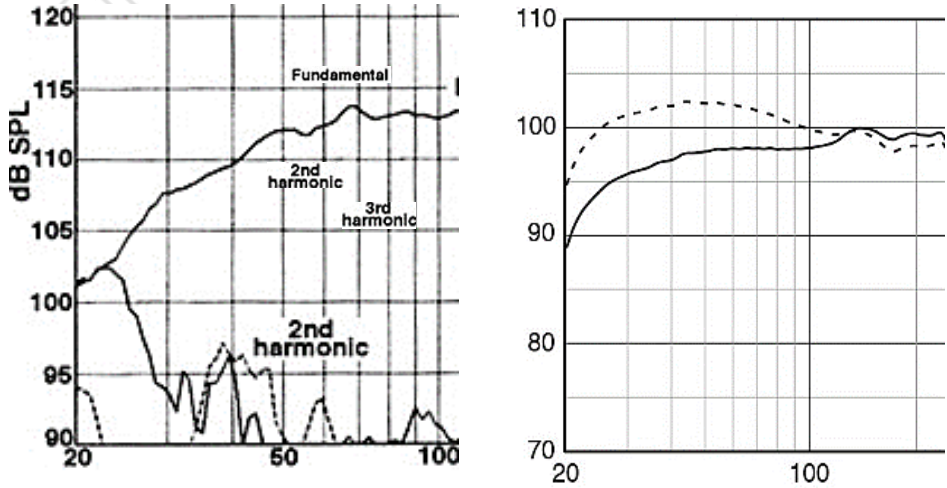


Fig.12 – L: Driver *bare* (before ported enclosure support) reaches 1/3 octave below *Fig.11* with still lower 0.5% THD. ***R:*** With enclosure set on the floor, SPL output **- - - -** is –3dB at 22Hz without EQ. When <¼ wavelength from one wall, add +6dB SPL. Add +5dB more by *VLF coupling* in dual-driver JBL 5628, each driver driven by a 2kw amplifier. Cinema SWs cross over at 80Hz, carry LFE to 120Hz, but are monophonic. [Data: JBL 2269.]
