Filmaker Technology White Paper

Subwoofer Camp

Robert E. (Robin) Miller III BSEE AES SMPTE
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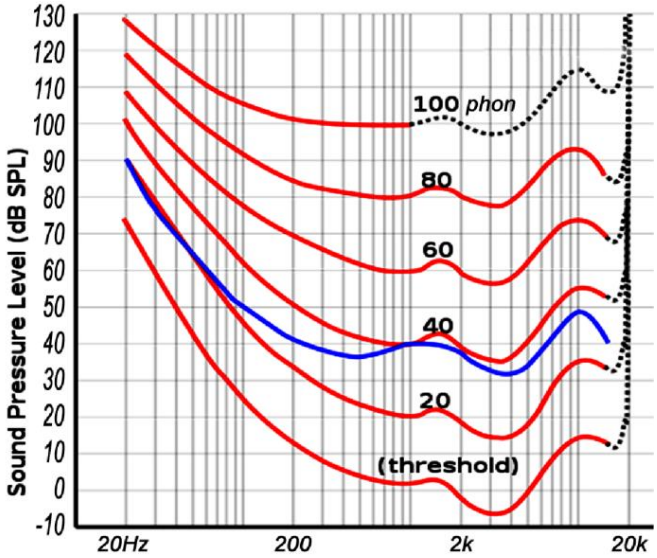
Even as we age, we will still enjoy rich low bass. However hearing lifelike low frequencies (LF) 20~200Hz, a third of 10 octaves of audibility, is not likely using bookshelf-size or even typical "tower" speakers alone. If we think we do, it may be distortion, which bass management does not filter. Actually hearing fundamentals of music extending to 30Hz, or movie effects to 20Hz, likely requires one or more subwoofers (SW). The key is Fletcher & Munson's work at Bell Labs in 1933, updated in ISO 226:2003.



Equal Loudness Contours of standard ISO 226:2003 show how hearing perception compresses bass frequencies, requiring higher SPLs to match loudness. The **blue** 40phon curve of Fletcher & Munson 1933 contrasts with the 2003 update, which inverted is approximated by the A-weighting curve used for noise measurements.

Can we know what we need if we haven't heard it?

The graph relates sound energy density (sound pressure level in dB SPL) and its resulting loudness perceived in the brain (in phon), showing it is not one-to-one. In our most sensitive hearing range 500~5kHz, each red loudness contour is roughly flat in dB-SPL. Each **red** phon contours label equates to its SPL at 1kHz. Vertically up the 1kHz line, each 1dB change in SPL causes 1dB-phon change in perceived loudness. For the subjects sampled and averaged in these studies, at the frequency extremes the sensation of loudness weakens, requiring ~14dB stronger SPL at 10kHz. However below 500Hz, the red loudness curves compress more and more, requiring greater and greater SPL. In the SW range below 120Hz, the slopes are a steep 20dB/octave at a quiet 20phon, but only half as steep, ~10dB/oct, at a loud 80phon. So at 20Hz, where only 55dB from 73~128dB-SPL spans the full 100phon, each 1dB change in SPL causes ~2dBphon change in perceived loudness! It's how we hear in life; it's what we want to hear from recordings reproduced in high fidelity. *But many audiophiles cannot know they have not fully heard low bass!*

Where at mid-frequencies a sound level change of ~10dB is perceived as a doubling or halving of loudness, *in the SW range doubling or halving loudness happens with only ~5dB SPL change!* Lower by -10dB, as many manufacturers specify "frequency range," is perceived as half loudness and half again, or only a quarter as loud. As we are doubly sensitive to low bass changes, we ought to consider doubly critical LF speakers and their adjustments. Be doubly attentive to avoid "thin" sound (weak in all bass), tubby (over-emphasizing bass), or HF either too bright or dull (bass under- or over-powering higher frequency sounds). Prepare to allocate budget for low frequency acoustic treatment. And be aware positioning SWs adjacent to a wall, wall+floor, wall+floor+wall that each doubles SPL by 6dB. [Cf. www.filmaker.com/papers.htm "Physiological and content considerations for a second low frequency channel for bass management]

The Equal Loudness Curves provide special insight into the subwoofer range from 20Hz to 63, 80,100, or 120Hz. Follow the "threshold" curve (the softest most of us can perceive) until it intersects a 30Hz tone (to cover the lowest Bb of a piano or the open B of 5-string bass) at 60dB sound pressure level (SPL). If heard live at a moderate 63SPL, it should be just audible. But reproduced over a loudspeaker advertised as having a "frequency response ±3dB to 30Hz" (–6dB), it plays 3dB shy of 60SPL, and be *inaudible*. At multiples of the fundamental frequency, harmonics including distortion may sound louder than the fundamental tone, if even audible. And cause us only to *think* we hear low bass when we don't…

Our brains deceive us when we *perceive un-hearable* fundamentals by virtue of higher harmonics that *are heard.* For centuries, organ makers have practiced this trick, reducing pedal pipe sizes by 2/3 playing a 3rd harmonic for listeners' to conjure fundamentals.[1] How? We've seen that with diminishing LF sensitivity regardless of speaker limitations, we may *not* hear 30Hz until at least 60SPL (its loudness still below zero phon). But at 60SPL we *are* able to hear a 2nd harmonic at 60Hz sounding like 20phon loudness, or a 3rd harmonic at 90Hz sounding like 37phon. Heard together, both "imply" a unique fundamental at 30Hz, which our brain *fills in* (perceives). Play fading out a low string or contra bassoon; at some level the fundamental becomes inaudible, however the perceived tone color does not change, because that fundamental is being "filled in."

Isn't this just how we hear LF live? Yes, but to preserve lifelike quality from recordings, reproduction must be flat in overall frequency response, and be equal to the mix SPL. A disparity can occur when during recording at an industry standard 85SPL, bass is deemed *normal*. But then in home replay, typically lower by 10dB at 75SPL, low bass will be weaker by –6dB at 30Hz – less than half its perceived loudness when recorded – calling for 6dB in *Loudness Compensation*. Or ~20dB when played as background. Conversely, bass played louder than mixed will be perceived as too much.

Harmonic distortion (HD) & inter-modulation distortion (IMD)

Distortion is where loudspeakers have the hardest job in high-fidelity, especially with subwoofers tasked to deliver very low frequencies at very high SPL. Referring again to the loudness contours, a 30Hz fundamental that is just audible at 60SPL *could be equaled in loudness by its own 2nd harmonic when weaker by 25dB.* Sounding as loud as the fundamental, this 2nd harmonic sounds like 100% distortion. Although, at -25dB, it is only 5% of the fundamental's level. We might perceive a double bass

[1] A "Resultant" or "Mutation" stop. While 3-inch smart-speaker cannot reproduce audible 60 (or 50) Hz utility hum, we recognize it from only its 2nd & 3rd harmonics at 120 (100) &180 (150) Hz. Manufacturers & recordists make music sound OK on bass-deficient boom boxes or desktop speakers, e.g. emphasizing a Fender bass' louder than fundamental harmonics.

Continued overleaf…

colored too bright. And as odd harmonics prevail with speaker drivers at very LF, a bass viol played louder and louder will take on a reedy timbre.

SW's with published percentages of distortion regarded as "normal" for higher frequency sounds mean low bass tone color will be falsified much more than expected. Consider the challenge of a "good" consumer SW measuring a typical 5% HD. 5% at 30Hz might be perceived the same as a poor amplifier at mid-range producing 100% HD! Per ISO 226:2003, to achieve 1% distortion (the definition of a high-fidelity component), the SW would need to measure 0.05% at 30Hz! In contrast the best studio-quality subwoofer in the author's experience measures 0.5% distortion, altering tone color far less, yet still sounding like 10% at mid-range. Whether for studio or home, the need for very low distortion is critical for subwoofers. But our exploration thus far describes only harmonic distortion (HD)…

Where there's HD there's likely *inter-modulation* (IMD), by which two pure tones produce sum & difference frequencies. These artifacts are not harmonically related, so are not "musical," but are alien "clang" or "burr" sounds accompanying any two tones, *even if one or both are not audible!* Take two C-extended double bass viols playing D1 with vibratos sounding between 35~38Hz. These fundamentals may not be audible, but quite audible is a random IMD sum product at 73Hz. You may think a saving grace for pop music is that there is typically only one bass note playing at a time. But combinations of that single note's harmonics or HD artifacts add spurious IMD products: sum tones at 108Hz, 111, 143, 146, 149, 181, 184, 219Hz, etc., plus infrasonic difference combinations that might even risk overloading a SW. These artifacts add up to bogus tone coloration.

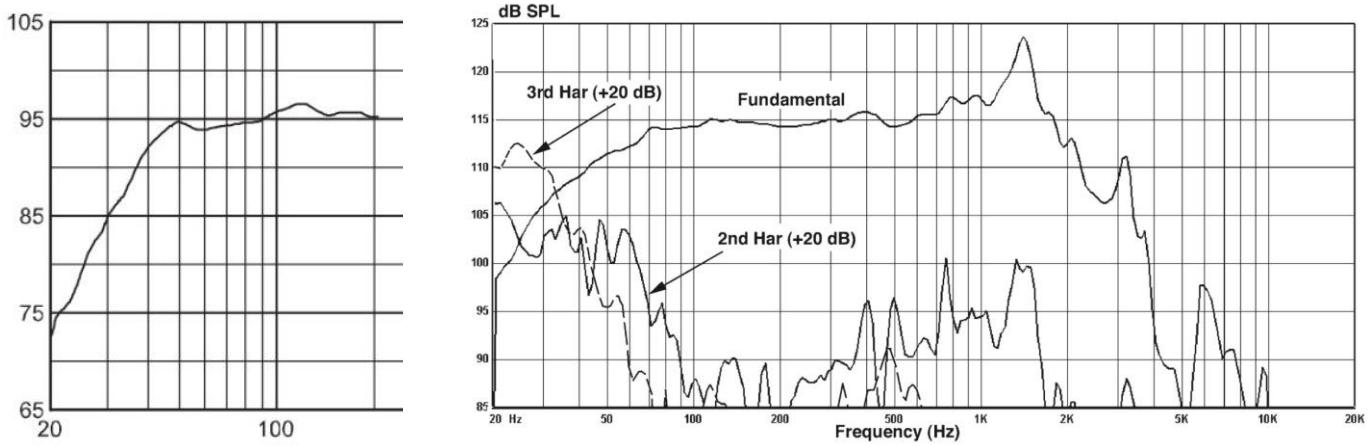
SW(s) must be heard but not "seen." HD & IMD distortion products are downstream of bass management, so can call attention to the SW, making "splicing" to main speakers difficult. The best solution to these issues is a low distortion subwoofer, don't push it, and perhaps use two (or more).

Conclusion, and what's next?

Low bass is difficult to hear, and to convey with purest tone color, the holy grail of high fidelity. Because perception is tricky, many audiophiles are not aware they haven't heard authentic low bass, therefore can't know whether they need to augment their main speakers with a subwoofer(s). A dilemma for producers & recordists is: "Do we use consumer-grade subwoofers in order to anticipate our recordings' sound at home?" The same question caused studios to install cheap monitors to anticipate "common quality." Then Toole at Harman found the average of many cheap consumer speakers was an excellent speaker! So savvy engineers use only their best monitors to make the greatest number of consumers happy. It remains whether this history repeats itself vis-à-vis SWs.

For as much as loudspeakers have improved in frequency response and distortion since the advent of hi-fi in the 1950s, they remain the audio components with the furthest to go. Still lower distortion SWs are needed. Even so, the most satisfying listening normally calls for using subwoofers.

Preparing to test a pair of commercial 18in subwoofers with very good frequency response and distortion data, below. Operated below their design maxima, SWs exhibit distortion falling much faster than SPL. [photo Filmaker Technology]



Left: Given a boost in low bass by ducted port enclosures, the frequency response of subwoofers above is down -3dB at 40Hz at 95SPL/1w/1m (no equalization). *Right:* Even at a very loud 115SPL, they exhibit low 2nd & 3rd harmonic distortion (raised 20dB), showing at 70Hz less than 1% of the more musical 2nd harmonic and <0.2% of the less musical 3rd harmonic. At more moderate home entertainment levels, distortion drops greatly to 0.1% and lower. [data courtesy JBL Professional.]

Robin Miller has presented his work to the Audio Engineering Society, Society of Motion Picture & Television Engineers, Acoustical Society of America, Canadian Acoustical Assn, and German Tonmeisters VDT. His company, Filmaker Technology, engages in applied research, systems design & integration, and has a Patent for a system of full-sphere 3D recording & reproduction. He has published White Papers and two books: a memoir "American Radio Then & Now," and for vinyl hobbyists to pro archivists "The Better Sound of the Phonograph."

[i] White Papers" are brief educational, semi-technical surveys on practical topics. Scientific research papers, updates, and books by the author are at http://www.filmaker.com/papers.htm.

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