2010-01-1153

Low-Cost Audio for Automobiles

Richard S. Stroud
Stroud Audio Inc.

Copyright © 2010 SAE International

ABSTRACT

Much design effort is given to the development and tuning of high-end automotive audio systems. Typically, premium speakers, separate amplifiers and careful tunings are used to create very high audio performance levels. Lower cost vehicles and vehicles of lower trim levels often feature more ordinary speakers and no separate amplifier. This typically leaves a number of listeners with little option for enjoying adequate bass performance, improved stereo imaging, etc.

Small changes in acoustical component features and specifications can produce significant returns in spectral performance. Additionally, low-cost, powerful audio digital signal processing (DSP) has made its way into modern receivers. As the processing power of these devices improves, there are new opportunities for lower-level vehicles to produce customer-pleasing levels of audio performance.

This paper addresses issues facing designers of lower-end audio systems and proposes solutions for potentially vexing problems such as those caused by non-linear speaker excursion. Informal listening test results from expert and non-expert listeners are also included.

INTRODUCTION

The author has observed that much acoustic design and development activity is consumed by creation of premium audio systems. The result of this careful selection of parts, patient tuning and, most often, significant expenditures, is frequently quite pleasing.

The lower end of typical audio offerings is often given less funding and attention, and as a result is much less exciting to hear.[1] Typically missing are deep bass notes, even spatial presentation, smooth frequency response and adequate treble frequency extension.

> Some OEM's and OEM suppliers have recently informed the author that they do give more attention to base systems, and have provided data that shows the success of this work. One work achieved attributes like 44 Hz bass extension and 111 dB bass SPL. Modern base systems can be made to perform well.

The base 4-speaker system typically exhibits the poorer of these characteristics, with little bass, near-side imaging and weak treble. Moving up to the "Up-Level" offering can produce improvements, but often leaves much to be desired. Treble can be strident, frequency response still ragged, imaging is perhaps even more near-side biased, and bass is still less than satisfying.

With low-cost, powerful audio DSP devices and some acoustic considerations, these shortcomings can be largely mitigated. Bass can be dynamically managed. Midrange and treble can be smoothed. Imaging can be improved by phase management. Spaciousness can be improved by time delay, which can also improve and allow an increase in overall sound pressure level (SPL). In addition to DSP processing, low-cost acoustic measures can be taken to improve spatial and treble response extension.

Lower-cost systems will not often achieve the SPL produced by premium systems. The author's experience suggests that most listening is done at moderate SPL levels and that strong customer satisfaction can be achieved without the capability for <110 dB bass, etc. The techniques in this paper include consideration of SPL, but focus mainly on issues important to moderate listening levels.

Some options available to the non-premium audio system designer are now discussed.

LOW-COST AUDIO SOLUTIONS

The receiver-amplifier, the speakers and the speaker installation can all contribute to excellent sound production in low-cost audio systems. It is important for the target characteristics of a high-performance, low-cost system to be understood by the system designer.

GOALS OF A LOW-COST AUDIO SYSTEM

The designer has sufficient options to enhance the performance of low-cost system options. Using inexpensive DSP techniques, giving some attention to speaker design, and providing a proper installation can narrow the performance gap in ways the consumer is likely to find enjoyable.

As an example, low frequency extension of a premium system may extend below 20 Hz. Perhaps this is not necessary for reasonable acceptance. Low E on a four string bass is 41.2 Hz, and a system that extends down to this frequency will please many consumers. Also, it is the author's belief that many listeners will be satisfied with moderate SPL capability if they can still hear bass notes above the noise floor.

Looking at specific attributes, the following low-cost system targets are now suggested:

- Spectral: Response is better than -3 dB at 40 Hz and 15 kHz, not including bass-boosting loudness compensation
- Spatial: Center images are positioned closer to the vehicle's dash center or in front of driver than to the near-side speaker. Some sense of surrounding ambience is perceived.
- Sound pressure level (SPL): Level is higher than 95 dBA, and 100 dBC.

AUDIO PROCESSING FOR THE LOW-COST RECEIVER

Digital Signal Processing, or DSP, has brought powerful audio processing capabilities into the car radio. Prices have dropped to levels that make such power available to low-cost receivers (some DSP units are under $1 US). DSP support overhead is likewise more affordable due to supporting microprocessor evolution. DSP options available to the designer include spectral response, time and phase manipulation, as well as dynamic voltage level manipulation. Specific options are now detailed.

Equalization

Perhaps most important to pleasing automotive listening is a natural tonal balance. Along with quality acoustical elements, it takes equalization (EQ) to produce this tonal balance. It is highly unlikely that even a premium system's speakers and system installation will provide a pleasing, natural experience without EQ.

Modern DSP devices feature substantial EQ capability that the designer should employ. A somewhat simplified vehicle equalization curve might look like the one below (Fig 1). This EQ curve shows substantial bass and treble boost, which would likely be compensating for less-than-optimum acoustics (the notch shown in the center of the curve is typical of those often needed for door speakers).

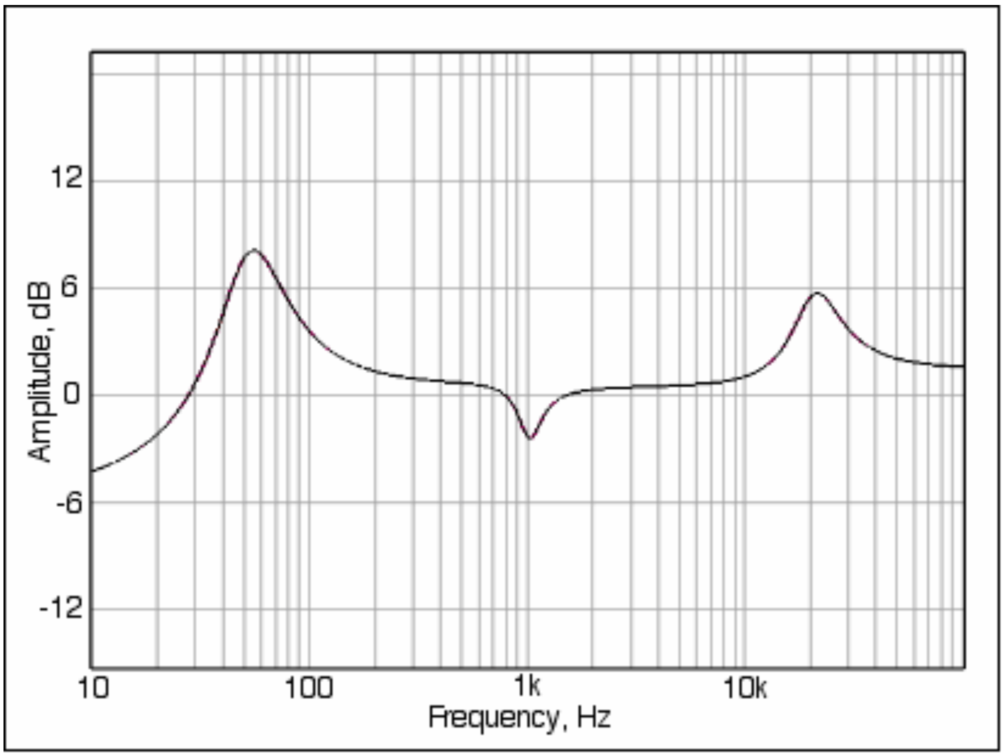


Figure 1. Simulated low-cost system equalization

A bass peak of 7 dB at 55 Hz would likely produce a headroom issue. For this reason, the loudness contours should feature a cut to reduce the effect of this peak at higher volume adjustments. Alternately, the some of the peak's boost could be reduced dynamically by a customized limiter characteristic (discussed later).

Note that there is a high-pass effect below the bass peak. This is used because strong signals below 40 Hz might cause unwanted artifacts in the system. Also, energy in the frequency range where the system's acoustics can't make good sound would consume headroom without a net benefit.

The treble peak of about 5dB at 21 kHz provides a treble lift in a region that contains little energy, and thus this uses little headroom. No dynamic EQ is needed here, except as needed to balance the tone when bass is reduced. To use this much treble boost, the system designer must make sure the FM system uses pilot tone suppression (most do), or this peak could emphasize a 19 kHz note that some would find distracting. As alternatives, 1) the FM system could use a different EQ from that of the rest of the system, or 2) a high-Q 19 kHz notch could be added.

The AM system could be subject to 10 kHz whistles, which the designer must check before finalizing system EQ. This is best done at night, when adjacent channels produce this note. Like the FM system, the AM system could have its own EQ (given the preponderance of AM talk stations, an EQ difference may be even more desirable).

Amplifier Power

Most OEM receivers today feature power amplifiers capable of driving four 4-Ohm speakers with 15-20 Watts. This power level is usually adequate for a pleasing sound production if bass management and other techniques outlined in this paper are used.

Time Delay for Rear Speakers

In many low-cost and premium systems, rear door speakers are employed for delivering sound to rear passengers. Often, these speakers are closer to the front passengers than are the front midrange speakers. To prevent pulling the image to the rear, designers must lower the gain of the rear speakers. This contributes to loss overall maximum sound pressure level and most critically, bass capability (see next section for more discussion of delay and bass).

The experience of listening to symphonic music in great concert halls is enhanced by the acoustics of the room. Side reflections are considered as desirable, and significant, treble-reduced and delayed returns from the rear likewise contribute to audience enjoyment. These features are found in acclaimed “shoebox” concert halls, which are found in many areas of the world (see Fig 2a and 2b).

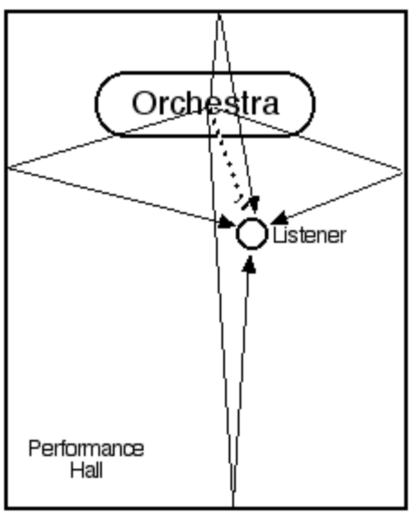


Figure 2a. Performance hall reflections

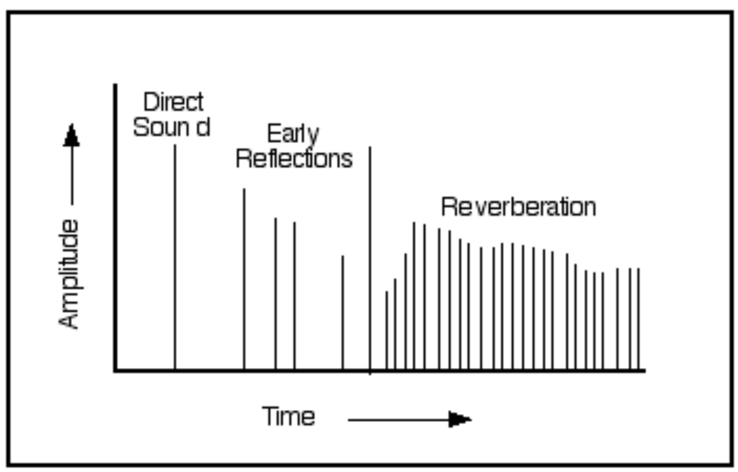


Figure 2b. Time domain captured in one channel

Capable stereo recording captures all these audible sounds, the direct sound and the space’s reflections. Many believe that quality stereo systems, which present these sounds from two speakers in a somewhat reflective listening space, can acceptably transport the listener to the performance space. The author does not share this opinion.

One can imagine that some kind of processed signal could manage this, perhaps using the head-ear properties of a given listener. If the listener were allowed head movement, spatial realism would suffer. Adding more speakers, especially rear speakers, will likewise not likely precisely reproduce the performance spaces' characteristics. It should, however, come closer to this goal than two speakers in a room.

The author believes that a more realistic spaciousness is desirable in all reproduction environments.[2] In the automobile, acoustic time delayed returns are too short to contribute to spaciousness. Also, absorbing materials prevent any significant reverberant buildup.

Simple time delays can add substantially to the listening experience. Delays of 5-6 mS add spaciousness without producing notable listening artifacts. It may be surprising that such short delays can produce desirable effects,

The author hypothesizes that recorded direct sounds from the rear are masked by similar earlier arriving sounds from the front. Reverberant sounds in the recordings are not as well masked, as they are somewhat continuous. Thus reverberation and perhaps reflections in the recording are perceived as more surrounding. Performing anechoic recordings, then using simple delays to see if spaciousness is still produced, could test this hypothesis. This experiment will be left for another paper.

Note also that when time delay is employed, EQ should be revisited to preserve the tonal listening experience for the front and often also the rear passengers.

Bass Level/Distortion Control

Bass production is one of the most significant differences between low-cost and premium systems. For bass production, air must be moved by the speakers' cone excursion. Premium speakers feature higher cone displacement, this due to longer voice coils (Fig 3) and more linear suspensions (Fig 5). The speakers used in low-cost systems typically demonstrate low excursion capability due to short voice coil lengths and stiff, very non-linear suspension compliance (Kms). These produce voice coil force (BL) and suspension spring properties much like those shown in Figs 4 and 6.

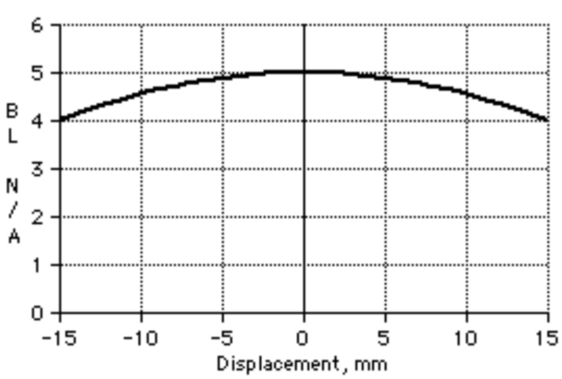


Figure 3. Premium speaker BL vs. X

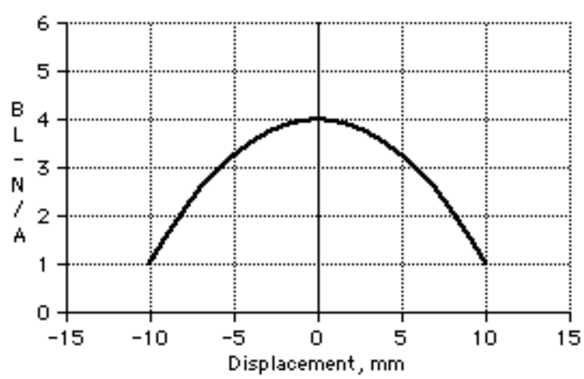


Figure 4. Low-cost speaker BL vs. X

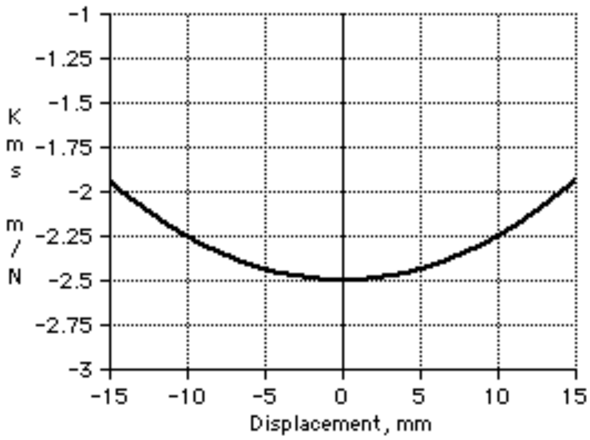


Figure 5. Premium speaker Kms vs. X

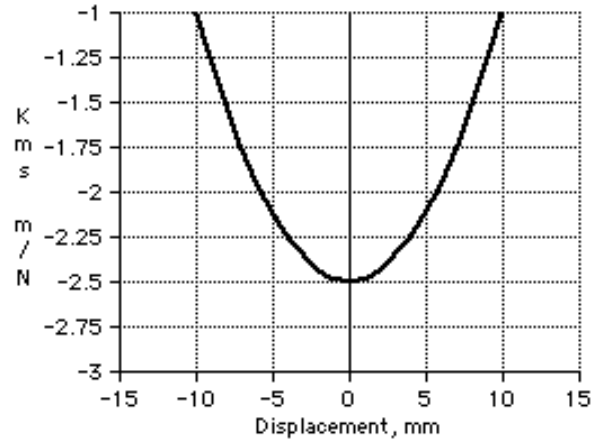


Figure 6. Low-cost speaker Kms vs. X

In order to produce the perception of stronger bass without objectionable distortion, audio signals driving these speakers must be managed so as to keep the speaker operating more in its linear excursion regions. This can be done in two ways. First, bass gain can be reduced at higher volume levels, which reduces the demand for excursion. Second, bass waveforms can be appropriately clipped and filtered.

Loudness Compensation is ostensibly used to adjust frequency response to match the human hearing characteristic, shown in Fig 7.[3] Typically used in car receivers are bass compensation curves like those shown in Fig 8.

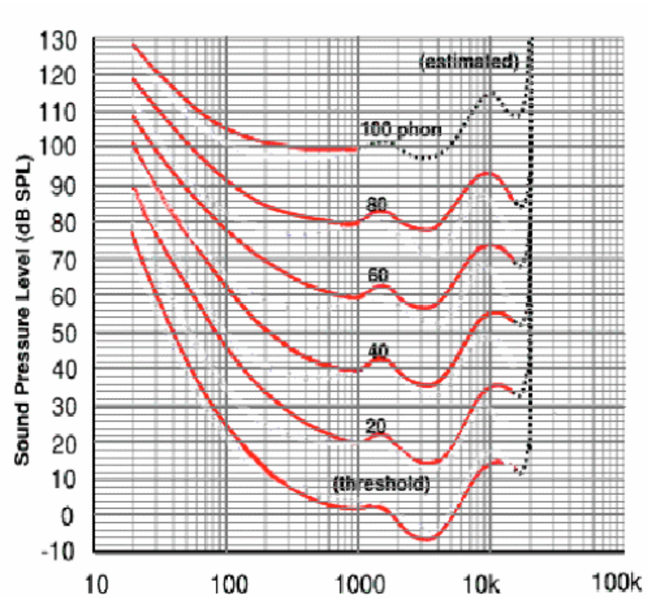


Fig 7. ISO226:2003 Equal loudness contours

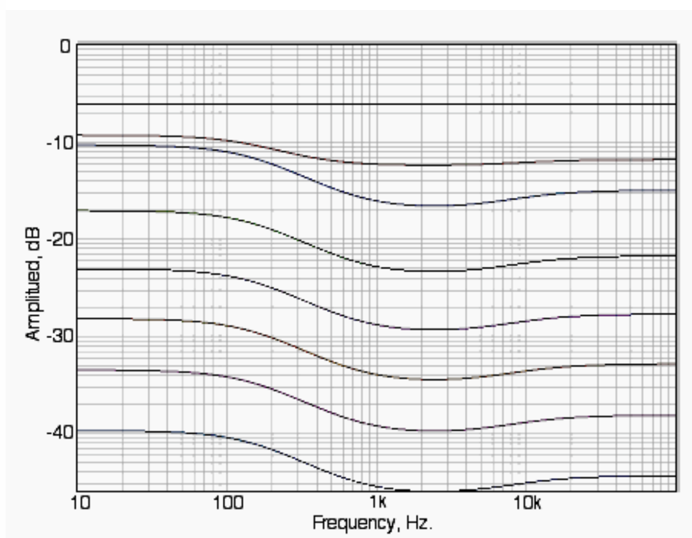


Fig 8. Receiver loudness compensation curves

For low-cost systems, this compensation can be modified so as to reduce bass at higher levels. Additionally, when high volume settings are adjusted, the bass control setting can be reduced to midpoint or even lower. Finally, and as mentioned earlier, bass equalization can be lowered as volume is raised. If this is all done gracefully, many users may not perceive a significant loss of bass performance.[4]

Using high-pass filters as high as 50 Hz, as the author has observed, to keep bass out of low-cost speakers does minimize distortion, but also reduces bass and is a needless loss to one listening at lower sound levels. This is not recommended for a static EQ, but could be part of a dynamic EQ system.

Clipping and filtering can add more perceived capability to the low-cost system. Much music that is played loudly contains strong peaks related to the beat of a bass drum or the release of a bass guitar string. These very tall initial peaks can be electronically clipped to minimize speaker "blat" sounds.

While this technique is effective for woofers, it can also be used to advantage with full-range speakers. The bass range frequencies can be routed through a clipper and low-pass filter (to minimize clipping artifacts), then recombined with mid and treble range frequencies with a summer (see Fig 9). In order to avoid frequency response anomalies, phase management of the two paths must be considered. Without direct comparison, it is the author's opinion that few low-cost audio owners will notice an objectionable loss of punch, and many will be pleased with the overall louder bass afforded by this setup.

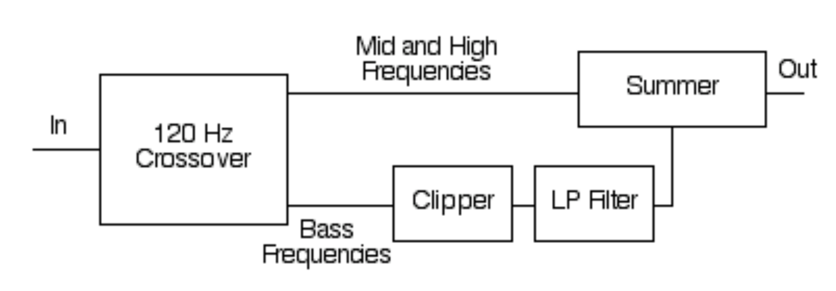


Figure 9. Full-range signal processing with clipping/filtering

Four door speakers are commonly used in low-cost automotive audio systems. These four speakers are typically capable of producing moderate amounts of bass. Front and rear door locations have acoustic transfer functions that transfer lower bass tones to the head in an efficient manner. Fig 10 shows the transfer function characteristics from various speaker locations of a 2003 Pontiac Vibe. Note that while the upper bass is not well transferred from most locations, desirable lower bass is efficiently transferred and is available to support bass production.

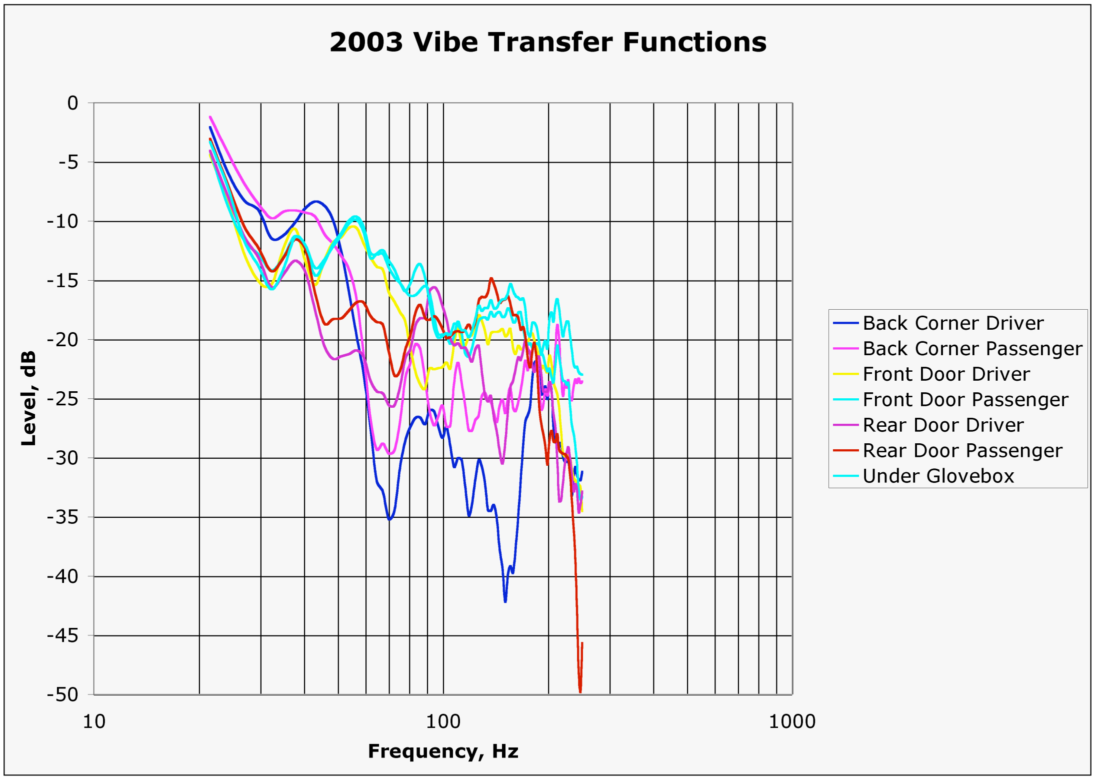
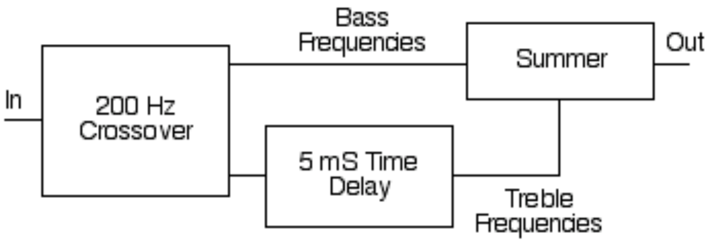


Figure 10. Transfer Function: 2003 Vibe

Unfortunately, rear door speakers are often adjusted to lower gain settings to maintain a front image for front passengers. The bass support opportunity is thus lessened. Fading front to rear could modify bass to improve this. However, having elevated bass in rear speakers exacerbates typically poor bass balance conditions for rear passengers.

As noted earlier, a time delay of 5-6 mS for rear speakers is sometimes used to improve the spaciousness of the listening experience. Adding this feature can benefit bass production. Delaying allows the level of the rear speakers to be raised without pulling stereo imaging to the rear. The rear speaker's bass support is thus available for all listeners.

A simple delay causes the rear speaker's upper bass to lose phase alignment with bass from the front speakers. It is thus necessary to implement a crossover-delay setup that does not delay the bass range, and "splices" the frequency response of the delayed upper frequencies seamlessly into the bass For example, a crossover of 200 Hz allows the low frequencies to blend with high frequencies that have been delayed one period, or 5 mS (see Figs 11, 12).



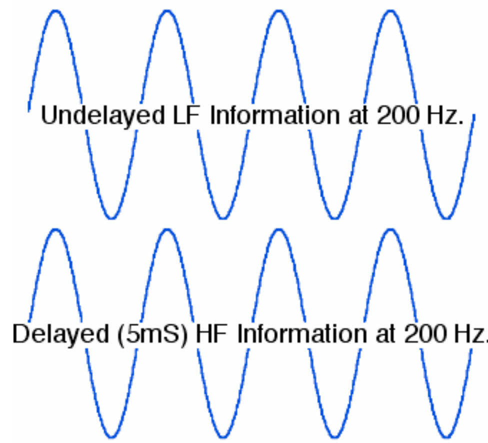


Figure 11. Time Delay Implementation

Fig 12. Phase match with 200 Hz, 5 mS.

This phase match can be accomplished for any time delay desired by shifting the crossover frequency and choosing a corresponding number of periods at that frequency. Note that half periods can be used as well, with either the lower or upper frequency range inverted in phase.

The author's listening tests indicate that delaying only those frequencies above the bass range is not detrimental to spaciousness. Crossovers higher than 200 Hz may prove quite acceptable for maintaining this spaciousness effect. The system designer should experiment with phase reversal of one crossover output, filter slope management, etc. to find the best combination of spectral smoothness and spaciousness.

Aligning Phase for the Driver

Stereo cues are sensed by arrival times, phase differences, group delays and intensity differences between the two ears. Faithful spatial reproduction is desirable, and most low-cost systems offer little in this regard. Drivers and passengers sit off center, closer to one stereo pair of speakers than the other. Most sounds seem to come from only the nearside speaker.

The designer can take advantage of the polar pattern of the low door-mounted speakers to do time-intensity tradeoffs at higher frequencies. A typical door speaker has a narrow polar projection that reduces the amplitude of treble range frequencies for the near listener. This performs a partial solution, often presenting an unfocused image somewhere along the dash.

The driver's nearside speakers, both front and rear, can be phase-aligned to improve focus and to move the image more toward the vehicle center.[5] The receiver's DSP should be capable of providing this function. A phase shift for the driver's speakers is adjusted such that the center image from perhaps 200 Hz to 500 Hz is perceived as centered (see Fig 13 and 14). Note that these figures represent the acoustic signal at the driver's ears (driver seated on left side of vehicle).

> Why not use time delay? The delayed phase response generated by phase alignment is the same as time delay, except that here it only operates in the lower midrange where vocals interact with the ear's phase detection system. The author has never heard a driver's side time delay arrangement that doesn't degrade passenger imaging, but has found that phase alignment causes minimal imaging degradation for the passenger. In one phase alignment application, the author and customer noted that passenger imaging was actually improved.

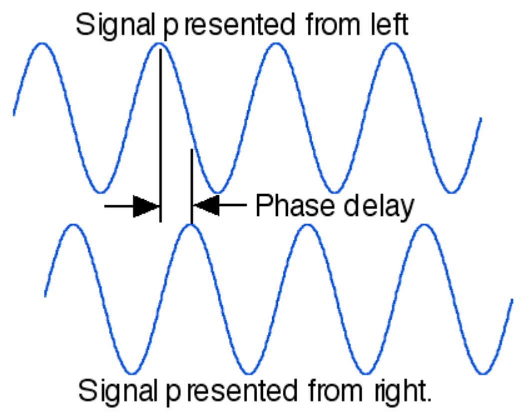


Figure 13. Phase condition without processing

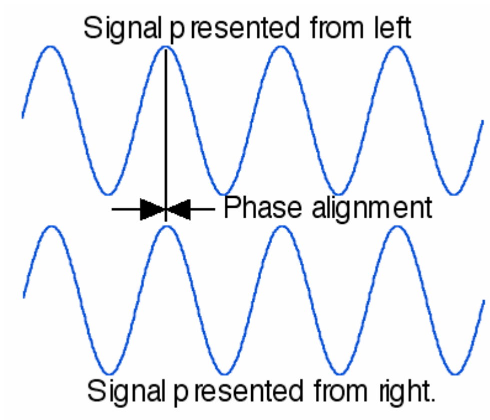


Figure 14. Phase condition with processing

Phase alignment can be accomplished by using an all-pass property in the driver's side channel. For software that does not offer an all-pass option, the addition of a frequency notch and a 180-degree out-of-phase peak of the same frequency can generate this property. Phase alignment, along with the time-intensity tradeoffs, can produce a convincing, better-focused center image for the driver.

ACOUSTIC SOLUTIONS FOR THE SYSTEM DESIGNER

More Speaker Issues

As mentioned, premium audio systems usually employ premium speakers that have excursion parameters that can produce strong bass. Also, tweeters and subwoofers are used to extend frequency range. The low-cost system cannot afford such components. Each corner of the vehicle must often use only a single midrange or dual-cone speaker.

Bass properties are influenced by the speaker's resonant frequency, f_0. Lower resonance tends to offer lower bass note production. In premium systems, most costly rubber and foam surrounds raise the speaker's compliance and thus lower f_0. Also, their separate woofers handle the low end and produce responses often below 20 Hz.

The low-cost system bass target of 40 Hz offers the designer the option of producing pleasing bass from the four "midrange" speakers. These speakers can use paper surrounds to keep costs lower. Paper surrounds can be so designed to soften speaker compliance, thus lowering $f_{0.}$ These surrounds can be treated by a lossy, rubbery compound to reduce reflections that can cause frequency disturbance.

> In the premium speaker, cost comes mostly from the need for a more powerful magnet to maintain sensitivity over the longer stroke. One could imagine a low-cost speaker with a longer voice coil / more linear suspension, but with smaller magnet and lower SPL capability. If the system designer can give up sound level for more linearity, this may produce a pleasing tradeoff.

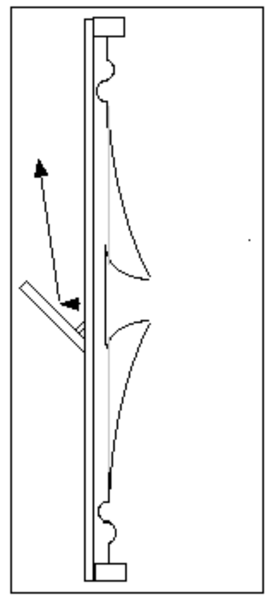
Also, as previously noted, a strong bass transfer function characteristic from all four door speakers is commonly available. Having four cones moving air allows even lower-excursion speakers to made moderately loud bass.

It is noted that the excursion produced by strong bass tones can cause intermodulation distortion (IM) of the midrange and treble notes. With proper speaker design, bass management and creative loudness compensation, this IM can be managed to the point that it is not noticeable on most popular music.

It might be desirable to aim door speakers upward to improve high-frequency output to the listeners. This, however, is seldom possible because of styling issues and leg space concerns. The treble radiating from a cone can be redirected from a speaker or grill feature (see Fig 15).

The so named "whizzer" cone used in dual-cone speakers offers high frequency performance at very low-cost. The whizzer produces a somewhat narrow beam of treble frequencies that is often aimed straight ahead into the passenger's legs. This can be re-aimed toward the ears with acoustic elements in either the speaker or the covering grill. These elements are positioned in the lower part of the treble "beam" and reflect some of this energy upwards.

Figure 15. Dual-cone speaker with treble deflector >



The size and shape of a deflecting feature determine how much energy is being redirected, where it is being redirected, and what frequencies are being redirected. A feature the size of a Popsicle stick would send upper treble in a new direction. Something more like a tongue depressor would send more of the lower treble as well as upper treble upward. Curving these features would cause more energy to be directed to a given listening space.

Sometimes, a dual-cone speaker system's treble beam will produce a "dead ear" effect. This is caused by a treble deficit that can be greatly improved with treble deflection.

> The speaker's moving mass is made heavier by the extra "whizzer" cone, and this reduces speaker sensitivity by 1-2 dB. Although the designer wants every dB that the system can produce, this tradeoff usually results in a net gain in performance.

In some cases, covering a portion of the midrange speaker's cone can improve stereo balance. It does this by improving the spatial distribution of frequency response. This may sound counterintuitive, but it can help in some cases.

<u>Grill, Mounting and Sealing</u>

Midrange speakers are typically mounted in the lower front of each of the four doors. This is a good location for both bass transfer function properties (mentioned above) and can be good for stereo imaging as well. It is important for any such speaker that the air path between the front and rear of the cone is as long and as well acoustically resistive as possible. Sealing the speaker to the door's trim panel usually does this.

Sealing to trim does not mean mounting to trim. The speaker's vibration is due to the recoil from the speaker's motor pushing on the moving mass's coil. This vibration often excites bass frequency modes on the trim and cancel bass production. It is important to reduce trim vibration by either 1) mounting the speaker solidly to a mass such as door metal or 2) float the speaker's mounting points from the trim with compliance, leaving only a tiny gap for vibration isolation. A very small gap does not notably reduce bass production. In fact, the vibration isolation results in a substantial net gain of bass in much of the bass region.

As mentioned earlier, treble redirection improves the spatial distribution of treble. This can be incorporated into the grill or into nearby interior surfaces. Manipulating these kinds of features can tailor frequency response in near and far side spaces to enhance time-intensity tradeoffs and improve stereo imaging.

Note also that the volume of air behind the speaker must be adequate to avoid excess raising of the door speaker's resonance. Even a tight film of plastic can reduce bass in this manner.

IN-VEHICLE DEMONSTRATION

Informal listening tests were performed on the author's 2003 Vibe. This vehicle has been modified to include a flexible, computer-based audio installation. Equalization and other electronic manipulations are done with a computer and audio software (Ableton Live). Formal listening tests with trained listeners would be required to draw firm conclusions about this system, but the author was more interested in observations relating to the electronic processing options detailed in this paper.

This modified Vibe is equipped with four 6.5-inch door speakers, two small mirror patch tweeters and two 12-inch woofers in an improvised parcel shelf. For this paper's tests, only the four OEM style 6.5-inch door speakers were used. These speakers feature treated surrounds and larger magnets than would be typical for a low-cost system. Magnet size would mainly affect available SPL; other differences would be corrected in EQ. To make the listening test more appropriate for this paper, high SPL listening was controlled. The front door speakers are of single cone construction while the rear door speakers are of dual cone design. No reflecting acoustic features were used.

The current speakers are known to produce a "blatting" sound on strong bass peaks. They were not designed to operate without a subwoofer. The front speakers were not designed to operate without a tweeter.

DSP features used were equalization, bass clipping-filtering (using an 80 Hz crossover), driver's side phase alignment and time delay (5mS.) for the rear speakers. The single cone front speakers required an unusual 27 dB of treble boosting, mostly above 10 kHz.

Listening tests were performed using the author's "Skilled Listening CD" in the stock Delphi dash receiver. Gain of the system was adjusted to somewhat appropriately use the receiver's loudness curve, although the curve's bass boost gain rise seemed a bit sudden for this application. There was no comparative experiment performed, and no experimental data taken. Finally, the vehicle was not driven during testing, except for my wife and myself.

The author's own listening tests noted smooth response, lacking a bit at both frequency extremes. There was some "boomyness" on the Beach Boy's "Kokomo" track. Bass was adequate at 40 Hz, but didn't seem to have the full "bottom" sound that a woofer could provide. Bass of frequencies lower than 40 Hz was not audible when driving. The bass clipper's distortion was audible on earlier tests, but not noticeable to me on music with final clipper adjustments.

Imaging on jazz and classical bands seemed spread across the dash, and was pleasing. Vocals were unfocused and spread from close by the near speaker over to the vehicle center. More development of the phase alignment and the use of dual cone speakers might improve imaging. The sound was quite spacious, and there was no rear pull. Even in the back seats, the sound seemed to come from the front of the vehicle. There was some occasional door rattle in the right rear door.

There was "hollowness" to the sound in the rear seat. I suspect the bass-delayed mids crossover was creating a high-Q frequency notch at the crossover frequency. Spectral smoothing will likely be improved by 1) putting one channel out of phase and 2) using lower Q crossover slopes.

The author expected the extensive treble boost for the front speakers to produce a compressed sounding treble and intermodulation distortion. This was not observed. The sound was surprisingly natural on some music selections. I prefer the resulting sound to that of many premium systems I have auditioned. To state the obvious: I am hardly a neutral observer.

Five other listeners auditioned the experimental setup. One listener was trained and experienced, three were musicians and one the author's wife. Their comments were as follows:

- Trained listener: Requested small upper bass EQ change, which was done. (Expletive) good base system. Very good sound. No real complaints.
- Musician one: Listened for longer time, did not want to leave. Likes spaciousness.
- Musician two: Liked "feel" of system. Liked being inside the sound. Hear the image as beside and slightly above him. Commented that bass and treble is "all there".
- Musician three: Was aware of cost-reduction activity regarding the sourcing of Vibe speakers, was convinced by bass production that the stock speakers had been changed.
- Author's wife: Wants this surrounding sound in our home. Would like to have our van's premium 8-speaker plus subwoofer system modified to have this surrounding sound.

SUMMARY/CONCLUSIONS

Techniques such as the ones described in this paper can help the designer produce a sound system that can provide high customer satisfaction. One may wonder if having such a system in your lineup would not cannibalize sales of premium systems. This can happen, but this thought should be lightly entertained along with the thought of cannibalizing a competitor's vehicle by your providing an unexpected, pleasant listening environment in your now higher-value vehicle.

REFERENCES

1. Nousaine, Tom, Common Autosound Errors, presented at SAE World Congress, 10AE-0192, 2010
2. Stroud, Richard, Reference vs. Preference: The "Surround" of Surround Sound, presented at SAE World Congress, 2006-01-0481, 2006
3. International Organization for Standardization, Normal equal-loudness-level contours, ISO226:2003, 2003
4. Stroud, Richard, Loudness Compensation in Automobiles, presented at SAE World Congress 07AE-306, 2007
5. Kihara, Hisashi, "Binaural Correlation Coefficient Correcting Apparatus", U.S. Patent 4 817 162, Mar. 28, 1989

CONTACT INFORMATION

For further information about the design of cost-effective audio systems, please contact the author:

Richard S. Stroud
Stroud Audio Inc.
4707 Wexmoor Drive
Kokomo IN 46902-9596
+1 765 963 3030
richard1@StroudAudio.com

SAE Paper number 2010-01-1153 © 2010 SAE International. This paper is posted on this website with permission from SAE International. As a user of this website, you are permitted to view this paper on-line, and print one copy of this paper for your use only. This paper may not be copied, distributed or forwarded without permission from SAE