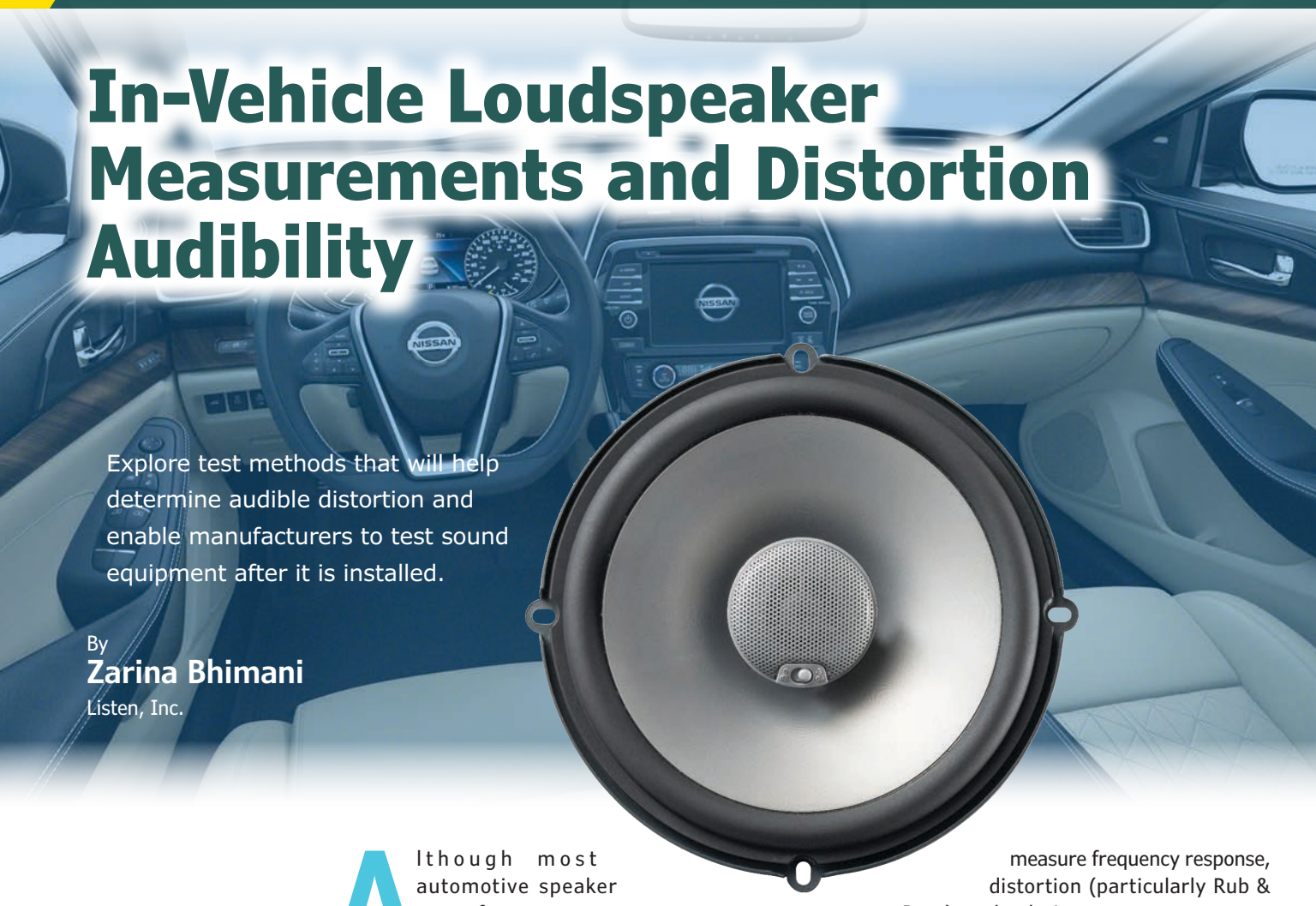
In-Vehicle Loudspeaker Measurements and Distortion Audibility



Explore test methods that will help determine audible distortion and enable manufacturers to test sound equipment after it is installed.

By
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Although most automotive speaker manufacturers carry out thorough end-of-line (EOL) driver testing (in many cases, 100% of product), many automotive manufacturers do not test the speakers once they are installed. It is possible for a speaker to develop a fault through damage in transit, handling, or installation. Furthermore, the simple act of installing a loudspeaker into a car can result in vibration issues caused by mounting and other components in the car.

Such issues can prove costly for automotive manufacturers. It is not uncommon for a car dealer to install a new set of speakers in a car if a customer complains about sound quality issues. It is, therefore, advisable for automotive manufacturers to invest in both incoming speaker QC and complete EOL testing of installed systems.

The test equipment for incoming QC and in-vehicle testing is similar to EOL production tests. In fact the test setup for incoming QC is practically identical to that used in driver manufacturing facilities worldwide (see **Figure 1**). This simple setup consists of an amplifier to drive the speaker, a measurement microphone, and software to measure frequency response, distortion (particularly Rub & Buzz), and polarity.

In-vehicle testing is implemented with similar equipment, but the setup differs in that the audio signal is transmitted from the measurement software via an audio interface to the auxiliary, Bluetooth, or USB input to the head unit. The test signal is played through the speakers, and the signal is picked up by a centrally positioned microphone. Care must be taken in positioning the microphone to ensure that the path from speaker to microphone is not blocked by seats or other parts of the car's interior. Usually the best position is on, or suspended above, the front seat arm rest.

A single measurement of frequency response and Rub & Buzz is usually sufficient to ensure that the audio profile measured in the car meets specifications. If there are discrepancies, each speaker can then be measured independently (including additional measurements such as polarity) to help identify the cause. Any microphones in the car (e.g., part of a voice control/telematics system) can also be tested using the same equipment and the car's own speaker to play the test signal (see **Figure 2**).

A similar test setup can be used for R&D testing (e.g., for voicing the audio system to the car). This might include speaker positioning and equalization of the system for correct tonal and spatial balance including left/right (L/R) and front/back balancing. It may also be used for microphone positioning and directivity measurements and noise cancellation performance.

Distortion Audibility and Objective Measurements

In a recent Audio Engineering Society (AES) paper called "In-Vehicle Audio System Distortion Audibility" (141st AES Convention, 2016), Steve Temme (Listen, Inc.) and Patrick Dennis (Nissan Technical Center North America) used such a system to research in-vehicle audio system distortion audibility and its correlation to objective measurements. The objective of this research was to identify the level at which in-vehicle audio distortion became audible and identify the objective test method that correlates best to human perception. Listeners evaluated three different audio tracks for distortion against defined criteria, objective measurements were made using a variety of test signals, and the correlation between the two discussed.

Listening Test

To determine the level at which distortion was audible and sound quality perception affected, binaural recordings of musical excerpts were made through the in-vehicle audio system at various volumes, adjusted to equal loudness, and played through a low-distortion reference headphone. Listeners ranked distortion audibility and perceived sound quality.

Three test tracks were selected: "Bird on a Wire" by Jennifer Warnes (female pop vocal), "Cousin Dupree" by Steely Dan (male pop vocal) and "American Boy" by Estelle with Kanye West (female/male hip hop). Each track was edited into short loops, normalized to 0 dBFS to ensure maximum gain, and transferred to a CD for in-vehicle playback.

Binaural recordings were made using a Head-and-Torso Simulator (HATS) and a BEQ II measurement front end in the driver seat of a Nissan Altima with a six-speaker audio system. The speaker arrangement consisted of two 3" speakers on top of the instrument panel (first-order crossed over at 1.2 kHz), two full-range 6.5" speakers low in the front doors, and two full-range 6" × 9" speakers in the rear parcel shelf. The head unit did not have electrical distortion limiting or compression. The recordings were made from volume step 20 to 40 (maximum) in two-step increments. This translates to a 1 dB/step change from volume step 20 to 22, a 2 dB/step change from volume step 22 to 34, and a 1 dB/step change from volume 34 to 40.

The binaural recordings were saved with direction-independent ear EQ applied, and each recording matched for overall loudness as well as

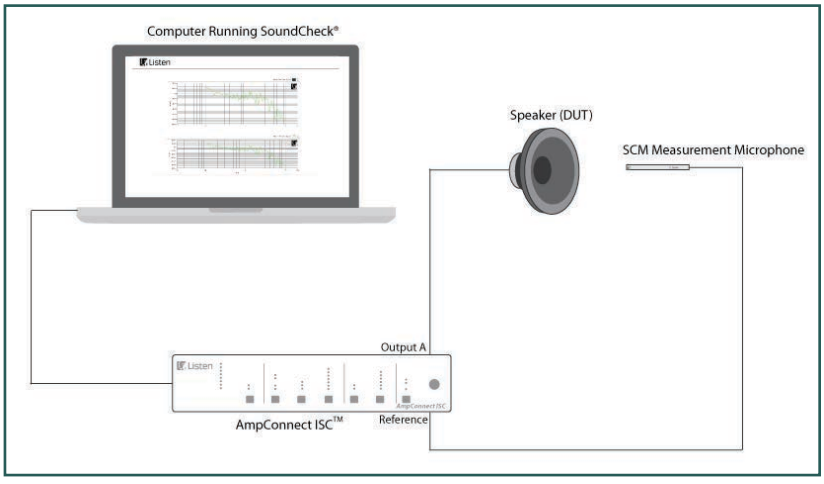

Figure 1: Here is a typical driver test setup for a production line or an incoming QC test.

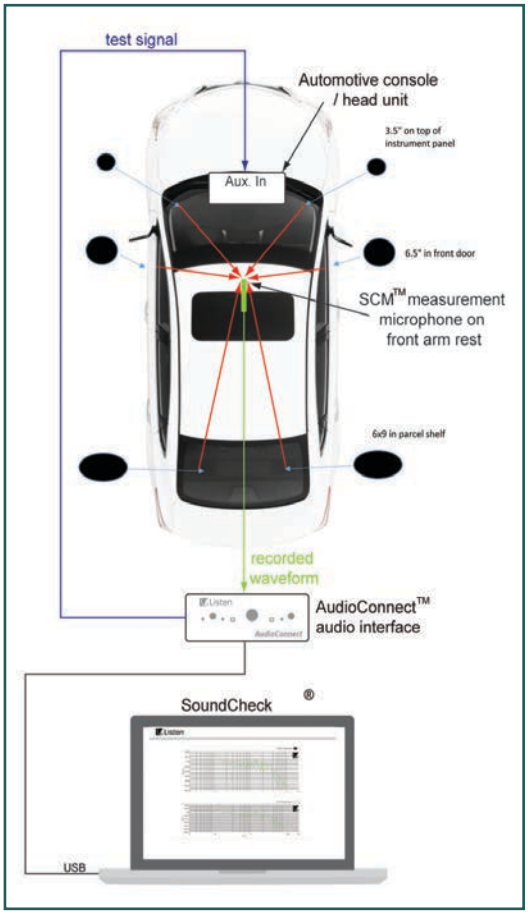

Figure 2: An in-vehicle audio measurement test setup is highly recommended.

Track	Volume Steps Used	Distortion Audibility
"Bird on a Wire"	34, 36, 38, and 40	Significant differences were found between volume 34 and 36, between 36 and 38, and between 38 and 40
"Cousin Dupree"	34, 36, 38, and 40	Significant differences were found between volume step 38 and 40 and between volume step 34 and 36. No significant difference was found between volume step 36 and 38
"American Boy"	30, 32, 34, 36, 38, and 40	Significant differences were found between volume step 30 and 32 and between volume step 32 and 34. Volume step 40, 38, and 36 had no significant difference found

Table 1: These are the results for our distortion audibility tests on three different music tracks.

spectrum in the bass region to offset the effect of dynamic loudness present in the head unit of the audio system. These adjustments removed the overall level and other frequency components, leaving only the amount of distortion as the distinguishing characteristic between recordings. The recordings were played back through a calibrated setup consisting of a programmable equalizer, headphone amplifier, and Stax SR303 headphones.

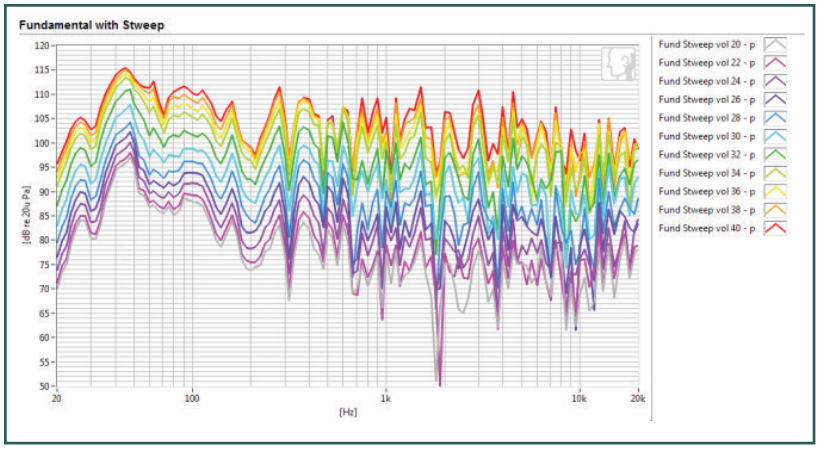

Figure 3: Fundamental vs. Volume Level (1/12th (R40) octave stepped sine sweep at 1 VRMS)

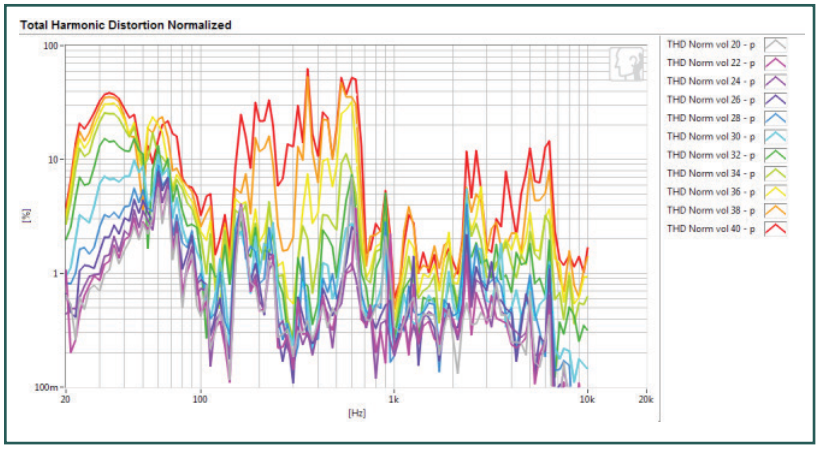

Figure 4: Total Harmonic Distortion Normalized vs. Level

The custom test GUI used a double-blind triple-stimulus with hidden reference system. Three audio tracks, the reference file, plus an additional reference, and the impaired file were simultaneously played back, with the listener able to switch between the tracks to compare distortion. The song and track presentation order were randomized. The participant identified which file had the impairment, rated the severity of the impairment on a five-point scale, and described the difference and the frequency range (bass, midrange and/or treble) in which the difference was heard. Twenty-eight listeners participated in the study.

Table 1 shows the distortion audibility results from the listening tests. Detailed statistical analysis validated these results.

Objective Distortion Measurements

A variety of objective distortion measurements were performed, using the test configuration shown in **Figure 2**. The digital test signals, created and played by the SoundCheck software, were passed through the AudioConnect audio interface for conversion to analog signals, and then amplified by the car audio head unit. A single Listen SCM3 measurement microphone—positioned on the arm rest between the driver and the passenger seats—measured the sound from the car audio system. The signal again passed through the AudioConnect (audio interface and microphone power supply) to convert the analog waveforms to a digital signal for analysis using the SoundCheck measurement software.

Objective distortion measurements were made with a variety of test signals: harmonic distortion using a swept-stepped sine; intermodulation distortion using two-tone intermodulation (one fixed and one moving tone); non-coherent distortion using pink noise; and non-coherent distortion (NCD) using the same tracks used in the listening test (see **Figures 3-10**).

The volume levels varied from about 75 dB to 110 dB SPL (see **Figure 3**). **Figure 4** shows the

total harmonic distortion (THD) and frequency normalized (THD Norm) measurements at the 11 different test levels, to remove the influence of the non-flat linear response on the harmonic responses and THD curve. Not surprisingly, this shows the THD increases with level—one would expect that at some point this distortion would become clearly audible and unpleasant sounding.

High levels of THD were observed at volume 32 and above (> 95 dB), especially at volume 38 and 40, which are approaching 60% THD at more than 100 dB SPL. This was very audible and mostly due to Buzz, Squeak, and Rattle (BSR). This is clearly visible in the Perceptual Rub & Buzz graph (see **Figure 5**), which represents how the human ear perceives high-order harmonic distortion (Rub & Buzz). It was hard to tell how much of the BSR was coming from the speaker or enclosure vibrations (e.g., door panels, center console, or rear parcel shelf), as everything was vibrating at these volumes. At volume 34 and under (< 100 dB SPL), the Rub & Buzz could not be heard.

The intermodulation distortion (IMD) graph (see **Figure 6**) shows considerable IMD centered above 1 kHz, probably because four of the six loudspeakers are full range and simultaneously trying to reproduce the low and high frequencies. This would likely be less in a multi-way car audio loudspeaker system with electrical crossovers, as the two tones would be played out of separate drivers. **Figure 7** shows non-coherent distortion using pink noise. It can be seen that the distortion consistently increases with volume level above 100 Hz.

Figures 8-10 show measurements of non-coherent distortion using the three sample tracks as the test signal. The data above 10 kHz is not too meaningful, since the selected samples did not have much high frequency content. "Bird on a Wire" (see **Figure 8**) had an average SPL for volume level 30 of 94 dBC. It can be seen that the distortion increased with level at 60 Hz (around resonance) and again between 200 to 2 kHz, but was lower from 70 to 200 Hz. This is probably because the car speaker was starting to compress the signal at low frequencies and move the energy to higher frequencies as Rub & Buzz. There was a jump in distortion level at volume level 34 and above.

"Cousin Dupree" (see **Figure 9**) had an average SPL for volume level 30 of 98 dBC. This track also demonstrated an increase in distortion from 60 to 120 Hz but is fairly constant from 120 to 180 Hz. There was a jump in distortion level, especially at volume level 34 and above from 500 to 2 kHz.

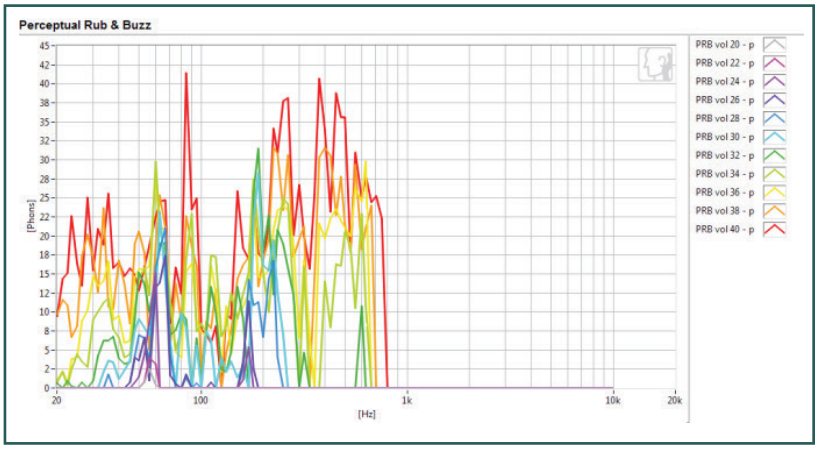

Figure 5: Perceptual Rub & Buzz vs. Level

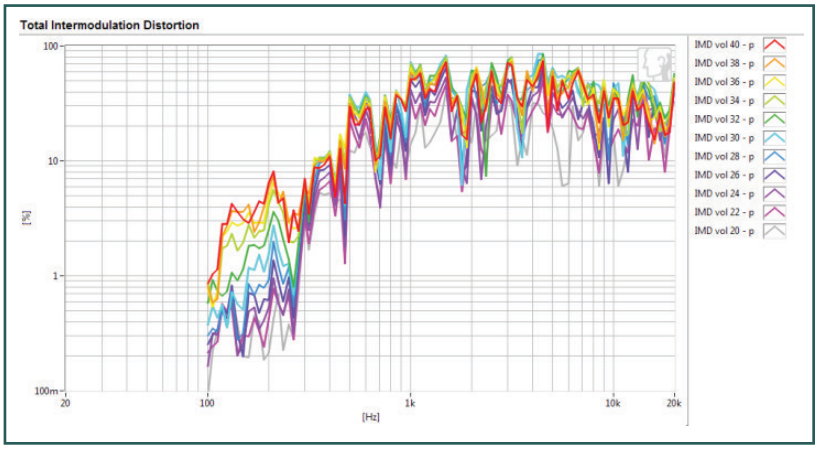

Figure 6: Total Intermodulation Distortion (IMD) vs. Level (one tone fixed at 60 Hz and 0.5 VRMS and the other swept from 100 to 20 kHz at 0.5 VRMS with 1 VRMS summed in phase)

About the Author

Zarina Bhimani has more than 20 years' experience in technical marketing, turning the words of scientists and engineers into readable feature articles. Most of that time has been at audio companies, including stints at Ferrotec and ALMA, as well as her current 10 years at Listen, Inc. This article is based on the work of Steve Temme and Patrick Dennis. Temme is president and founder of Listen, Inc., and an audio measurement expert with more than 30 years' experience and author of dozens of technical papers. Dennis is a principal engineer at Nissan Motor Company with more than 25 years' experience in automotive audio systems and sound quality.

"American Boy" had an average SPL for volume level 30 of a huge 105 dBC (see **Figure 10**). This can be explained by examining the time waveform of the original song. It looks like a square wave with a very small dynamic range). The NCD distortion measurement produced similar distortion curve shapes as with the previous songs but the distortion jumps at volume level 24 and above. This is probably due to the higher recording level.

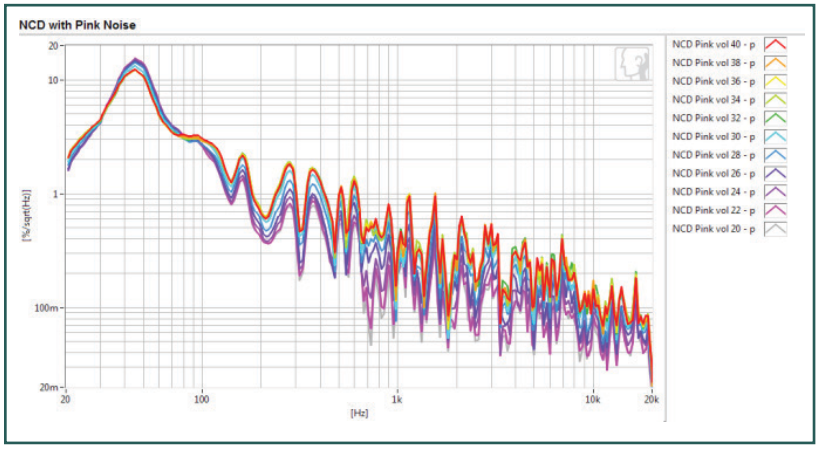

Figure 7: NCD (Pink Noise) vs. Level measured using 12th octave pink noise from 20 to 20 kHz at 0.5 VRMS (2.5 Vp).

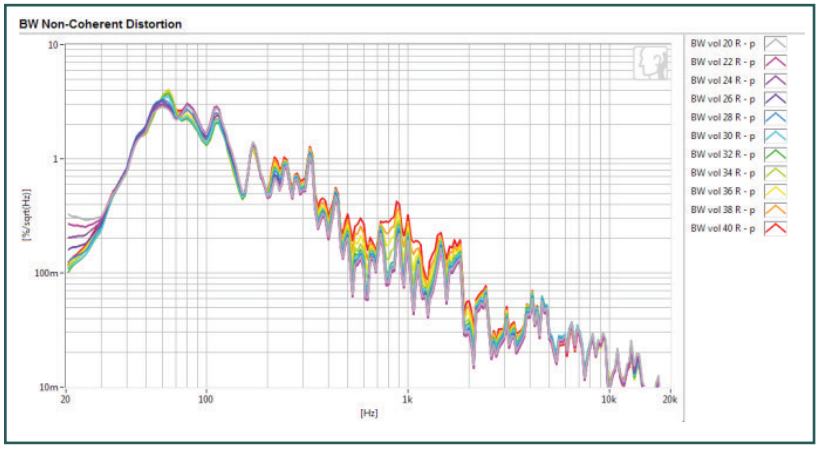

Figure 8: NCD ("Bird on a Wire" track) vs. Level

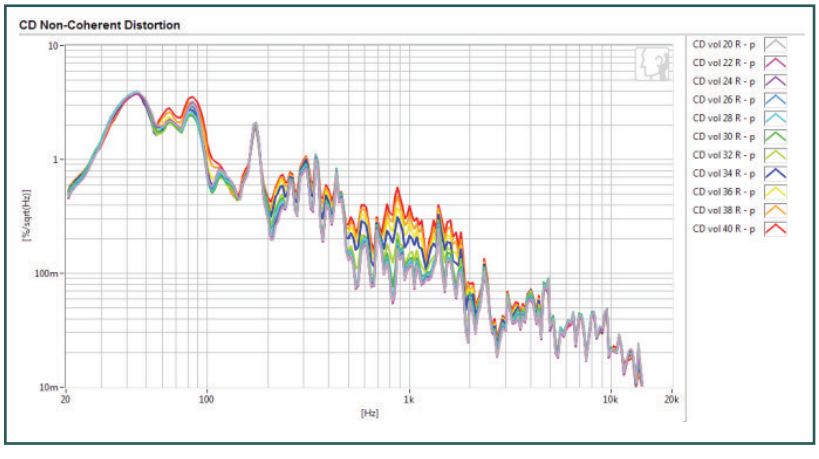

Figure 9: NCD ("Cousin Dupree" track) vs. Level.

Correlation Between Objective and Subjective Measurements

The results from the listening tests indicated listeners were able to discern audible distortion above a given threshold for different songs. For "American Boy," that threshold was quite low, from volume level 30 to 32, which corresponds to about 105 dBC. For "Cousin Dupree," the threshold was higher, volume level 32, which corresponds to 100 dBC. For "Bird on a Wire," the threshold was even higher, from volume level 36 to 38, which corresponds to about 100 dBC. Therefore, it appears that at volume levels of about 100 dBC or higher, distortion is clearly audible.

The THD measurements (see **Figure 4**) indicate that harmonic distortion, especially high harmonic distortion jumped above volume 32 (approximately 100 dB SPL). This is consistent with the subjective listening tests. It also indicates high levels of distortion throughout the entire frequency range, in particular, 20 to 80 Hz (around speaker resonance), 150 to 700 Hz, and 2 to 7 kHz. Listeners expressed that they heard most of the distortion in the bass and midrange frequencies. In summary, there appears to be a strong correlation between the amount of THD measured in the car speakers and distortion audibility.

The IMD increases at volume level 26 (see **Figure 6**). The IMD level is greatest above 1 kHz, in excess of 50%. This corresponds with listeners' comments about audible distortion in the midrange but not as well with the threshold of audible distortion, which most listeners heard at a higher threshold level.

The NCD measurements based on pink noise (see **Figure 7**) show a consistent increase with volume level above 100 Hz. The fact that distortion is not increasing as much in low frequencies indicates that it is spreading to higher frequencies. This should indicate that it will be more audible since it is far apart in frequency and will not be masked

The measurements for NCD based on music (see **Figures 8–10**) demonstrate that for "American Boy," the jump in distortion level at volume 30 corresponds well with listeners' perceived level of distortion. For "Cousin Dupree," the jump in distortion level at volume 32 also corresponds well with listeners' perceived level of distortion.

For "Bird on a Wire," the jump in distortion level at volume 36 once again corresponds well with listeners' perceived level of distortion.

In summary, NCD based on music correlates significantly better with listeners' preference ratings than THD, IMD, and NCD with pink noise measurements. It should not be surprising that this distortion metric produced the highest correlations since it used the same test signal (music) as used in the listening tests.

We suspect that even better predictions of audible distortion in music could be achieved if a psychoacoustic model was applied to take into account the masking properties of the music on audibility of distortion. This will be the topic of a future study.

Conclusions

The goal of this research project was to determine if there was a consistent distortion level vs. frequency at which distortion became audible, regardless of the music source material. If we take into account the difference in level of the music source material, this car audio system sounds noticeably distorted with most music above 100 dBC in the frequency range of 200 to 2 kHz and above 0.2% NCD.

It is likely that, at the higher volume levels, the car audio system is being pushed to its physical limits and creating lots of high order distortion or Rub & Buzz, which is quite audible and annoying. This is not surprising since the speaker cone excursion, and therefore distortion (especially odd order harmonics) is greatest at resonance.

Of the four distortion metrics measured, NCD using music as a stimulus showed the best correlation to human perception. Further tests are needed with other car audio systems and other loudspeaker systems including headphones and home speaker systems to investigate consistency with other car audio systems and other loudspeaker systems including headphones and home speaker systems to confirm that we can use the same NCD metric.

Finally, further research into adapting NCD to a perceptual model should be investigated. This may allow a common distortion metric across all sound reproduction systems to predict distortion audibility and subjective quality for human hearing. ***LIS***

Author's Note: Due to editorial space constraints, much experimental detail is omitted. For more information, download the full technical paper from www.listeninc.com/resources/published-papers.

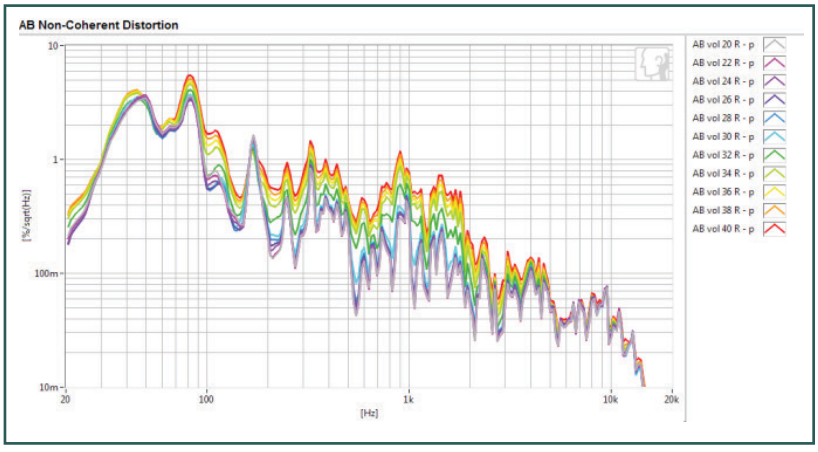

Figure 10: NCD Distortion ("American Boy" track) vs. Level. The average sound pressure level for volume level 30 was a huge 105 dBC.