MEASUREMENTS OF MULTITONE DISTORTION IN OCTAVE BANDS OF A CINEMA MIXDOWN LOUDSPEAKER SYSTEM

G Leembruggen Acoustic Directions, ICE Design Australia
A Mardikian Sony Pictures Entertainment

1 INTRODUCTION

1.1 General

For many years, distortion produced by electroacoustic systems has been measured in the forms of total harmonic and total intermodulation distortion. Traditional harmonic distortion measurements using a single test tone or sweeping tone are easy to execute but do not reveal intermodulation products and bear little similarity to music and speech.

More recently, Czerwinski, Voishvillo et al [1], [2] produced a comprehensive and detailed treatise on the use of a multitone signal to assess the distortion of sound systems. As a multitone test signal excites many frequencies simultaneously, it produces both harmonic and intermodulation distortion products and therefore provides a more rigorous test signal for measuring system non-linearities. Temme and Brunet [3] provide a discussion of multitone distortion measurements and note that system theory (Refs 3 and 4 in that paper) shows that more than two tones are needed to fully characterize a non-linear system.

In his loudspeaker testing facility, Goertz [4] uses sixty tones spread over the range of 20 Hz to 20 kHz. An application note prepared by Klippel Gmbh [5] provides insights into how multitone tests reveal different aspects of loudspeaker non-linearities. **Figure 1,** which is extracted from Kippel's application note [5], is a good illustration of the spectra of a wideband multitone signal and distortion.

However, Temme and Brunet [3] also highlight three disadvantages of multitone tone distortion measurements:

i. The number of intermodulation tones grows extremely fast with the number of stimulus tones.
ii. When power summing the distortion products, the individual distortion components and distortion orders are lost in the measurement.
iii. Careful selection of the stimulus frequencies is required so that they match the individual FFT bins in the analysis to prevent frequency aliasing.

1.2 Stimulus for this Work

The authors are members of the SMPTE's 27 CSS committee for Cinema Sound Systems, and this group recently initiated a project to better understand the reasons why some cinema soundtracks don't sound as good as they should. Part of this project was to undertake measurements of i) non-linear distortion and ii) loss of coherence in some cinema sound systems.

Given the ability of multitone test signal to excite many frequencies simultaneously, this distortion type was investigated for use in the cinema tests. Although the distortion components with the wideband multitone test signal are visible, there is no information to relate the input frequency bands to output distortion products. In response to this problem, the authors suggested using multitone signals in separate octave bands (OBs) to gain greater insights into the relationships between distortion and perceived sound quality in various sections of soundtracks.

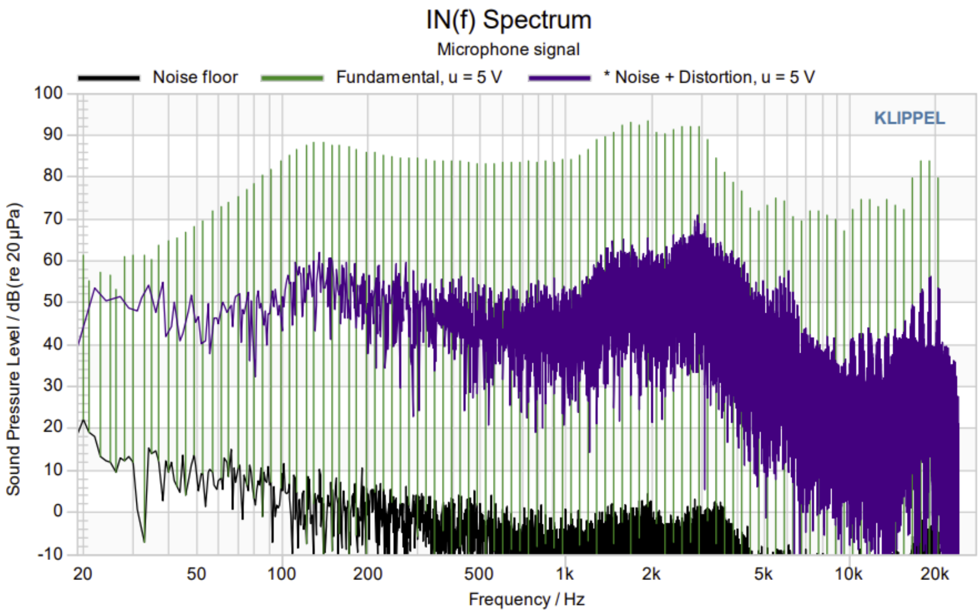


Figure 1. Example from Spectra of input multitone signal and distortion products (from [5]).

2 STRUCTURE OF THE TEST SIGNALS

a) The test signal consists of five-second-long bursts of ten tones in each of nine octave bands. Between each burst is a five-second-long gap to allow i) reverberation to die away and ii) analysis of the ambient noise that was present after each octave band burst.

b) To prevent overlap of harmonics and fundamentals in each band, the frequencies of the tones should be prime numbers. In the bands 63 Hz to 8 kHz, the frequencies are prime numbers and were selected for best consistency in the spacing between frequencies. In the 31 Hz band however, there were not sufficient prime numbers in the range 22 Hz to 44.5 Hz and frequencies were selected for suitable spacing. Table 1 lists the selected frequencies.

Table 1. Frequencies of the tones in each octave band.

Octave band	Multitone Frequency									
31.5	23	24.7	26.6	29	31	33	35.5	37	41	43
63	47	53	59	61	67	71	73	79	83	89
125	89	97	101	107	113	127	137	149	157	163
250	181	193	211	229	251	269	281	293	317	347
500	359	389	421	449	487	523	563	607	653	701
1000	769	839	911	983	1051	1123	1187	1259	1327	1399
2000	1423	1543	1663	1801	1931	2063	2207	2351	2503	2663
4000	2833	3089	3359	3643	3929	4241	4561	4889	5227	5581
8000	5659	6173	6701	7229	7757	8311	8861	9413	9967	10531

c) So that the test signal replicates the demands on long-term and short-term power levels of typical programme content, it is desirable that the temporal structure of the multitone signals is similar to that content. In its simplest form, the crest factor (which is the ratio in dB of the peak signal level to the long-term RMS level of the signal) should be approximately 12 dB or higher. This can be achieved by randomising the phases of the individual tones.

d) A random number generator was used to produce a set of ten randomised phase shifts. These phase shifts were applied to each of the ten tones, which were summed to yield the multitone signal. The crest factor of the composite signal was then computed and the process repeated three times. The set of phase shifts with the highest crest factor was selected and applied to each of the nine bands. Table 2 shows the selected set of phase shifts.

Table 2. Set of phase shifts applied to the ten tones.

Tone Number	1	2	3	4	5	6	7	8	9	19
Phase shift (Degrees)	63	75	-34	-117	169	-32	37	-92	-95	-158

e) The statistics of the composite tone signal are shown in Table 3.

(Kurtosis is a statistical measure used to describe the degree to which the levels in the composite signal gather in the tails or in the central peak of a frequency distribution. (The peak is the tallest part of the distribution, while the tails are the ends of the distribution).

The percentile levels of the composite signal in each OB are shown graphically in Figure 2.

Table 3. Statistics of the resulting composite signal in each octave band.

Octave band	RMS dBFS	Crest Factor dB	Kurtosis
31.5	-10	9.7	7.3
63	-9.4	9.3	8.1
125	-10.7	10.6	6.7
250	-9.9	9.8	6.6
500	-10.8	10.7	6.8
1000	-10.6	10.5	7.1
2000	-11	10.9	6.6
4000	-11.6	11.5	7.1
8000	-10.8	10.7	6.6

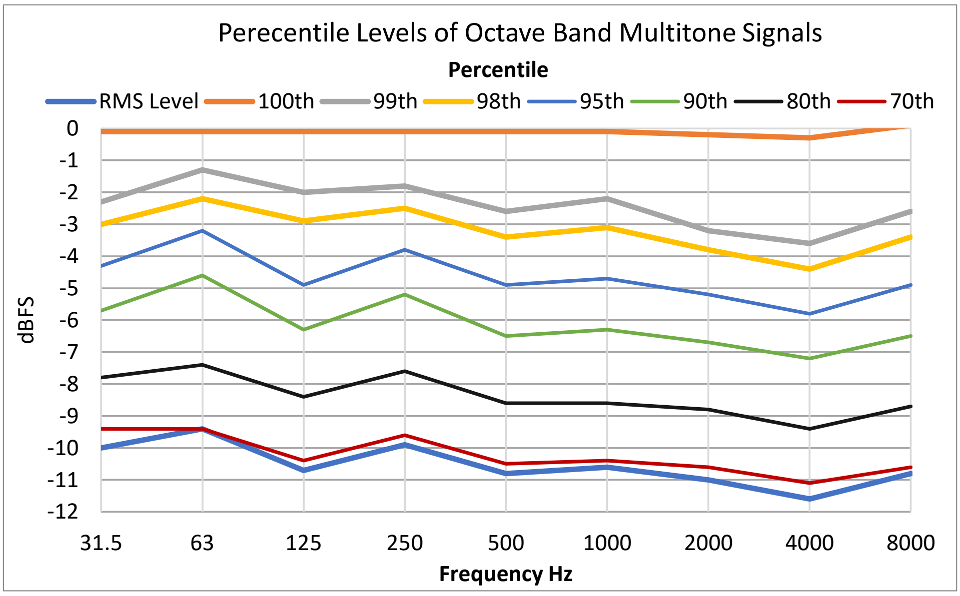


Figure 2. Percentile levels of the composite multitone signal in each octave band.

f) The amplitude of each octave-band composite signal was then adjusted to match the spectrum of the above-mentioned segment of the movie Transformers. The gaps were then inserted between each octave band multitone signal yielding a sequence of nine bursts of ten tones.

g) Three sequences were made and the overall level of each sequence adjusted so that the peak level in the sequence was -10 dB FS, -5 dBFS and -0.1 dBFS. This occurs in the 63 Hz octave band.

Figure 3 shows the temporal structure of the three sequences and the associated spectrograph.

Figure 3. Temporal structure of the octave band test signal after amplitude shaping.

3 TEST METHOD AND ANALYSIS

a) In the cinema, the sequence was replayed and recorded by a Type 1, 12.5 mm free-field microphone located at the Reference Position in the cinema. The gain of the recording chain (i.e., cinema SPL to recorded dBFS) was calibrated by imposing a 94 dB SPL calibrator onto the microphone.

b) The recorded file was separated into three separate sequences and then processed in MATLAB software. The MATLAB process functions as a single channel analyser, in which the analyser has no prior knowledge of the signal input. This imposes some difficulties as the multitone frequencies that are to be notched out must be removed using a “search and destroy” method, rather than setting notches at pre-determined frequencies.

This single channel method was used to prevent any misalignment in the sampling rates of the playback and recording systems from causing problems with pre-defined notch frequencies.

c) A Nutall window was used for the spectral analysis, which is a four-term Blackman-Harris window. The length of the Fourier transform was 1,048,576 points, yielding a resolution of 0.046 Hz.

d) According to [6], the Blackman-Nuttall window is useful for single tone measurement. Among the Blackman, Exact Blackman, Blackman-Harris, and Blackman-Nuttall windows, the Blackman-Nuttall window has the widest main lobe and the lowest maximum side lobe level. **Figure 4** from Wikipedia [7] shows the frequency response of a Nutall window that is N samples long.

e) The notches are implemented as simple attenuations at specific frequency points, with the bandwidth of the notches (i.e. the number of points being removed) increasing as the frequency decreases. This increase is necessary because the length of each OB signal (5 s) contains much fewer cycles at low frequencies than at high frequencies, which is equivalent to decreasing the window length. In turn, this decreasing window length increases the width of the primary lobe in the frequency response of the window, requiring removal of a greater number of points.

f) The analysis window is shifted along the time file in to coincide with each OB signal or the period of silence directly following each OB signal.

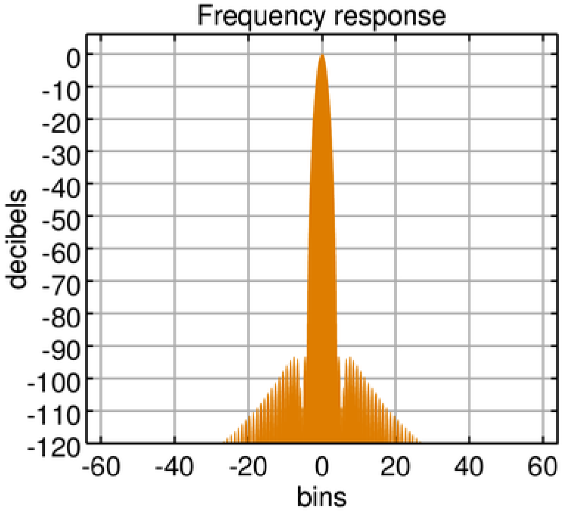


Figure 4. Frequency response of a Nutall window

g) The same process was applied to the period of silence between the OB signals, so that the ambient noise in the room could be separated from the combined residual (ambient and distortion) levels.

h) The spectral levels of the ambient noise in the five-second gaps and the residual distortion and noise were individually summed into narrow bands so that their total power levels could be compared. At frequencies in which the residual signal level was greater than the ambient level, the ambient noise level was logarithmically subtracted from residual signal level. If the reverse was true, the residual signal level was set to -100 dB.

i) The received multitone and residual signals were both integrated and the total distortion level computed relative to the received signal.

4 EXAMPLES OF DISTORTION OUTPUTS

Figure 5 shows the OB spectra for the test signal sequence with maximum level of -5 dBFS. Spectra shown are the raw received signal, the raw signal with the tones notched out, the ambient noise, and integrated ambient and residual signals. The total distortion in dB is stated for each octave band.

Figure 6 shows the same information as **Figure 5** for the test signal sequence with maximum level of 0 dBFS.

Figure 5. Octave-band spectra for the sequence with maximum level of -5 dBFS. Spectra are the received, notched, ambient, and integrated ambient and residual signals.

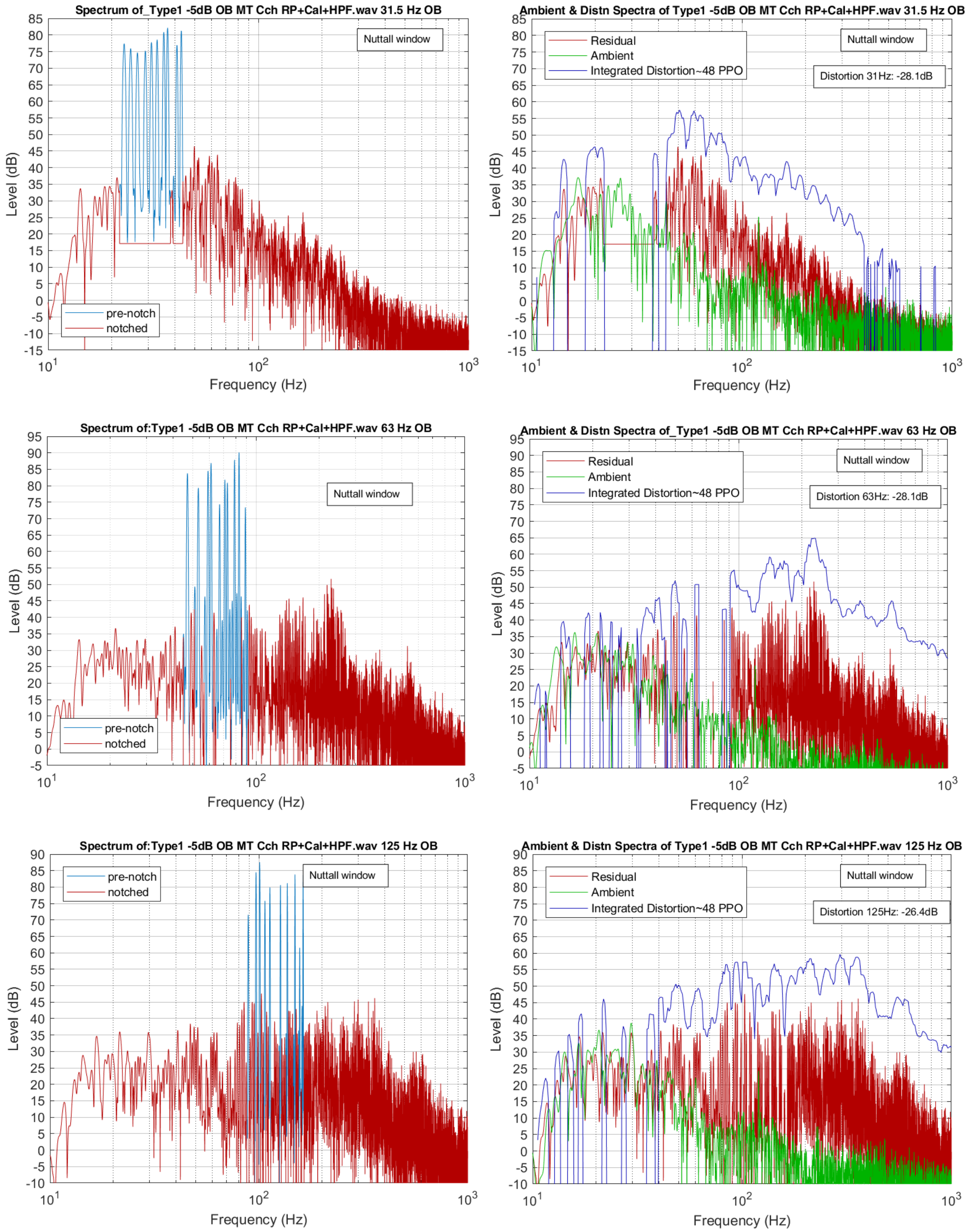


Figure 5 cont.

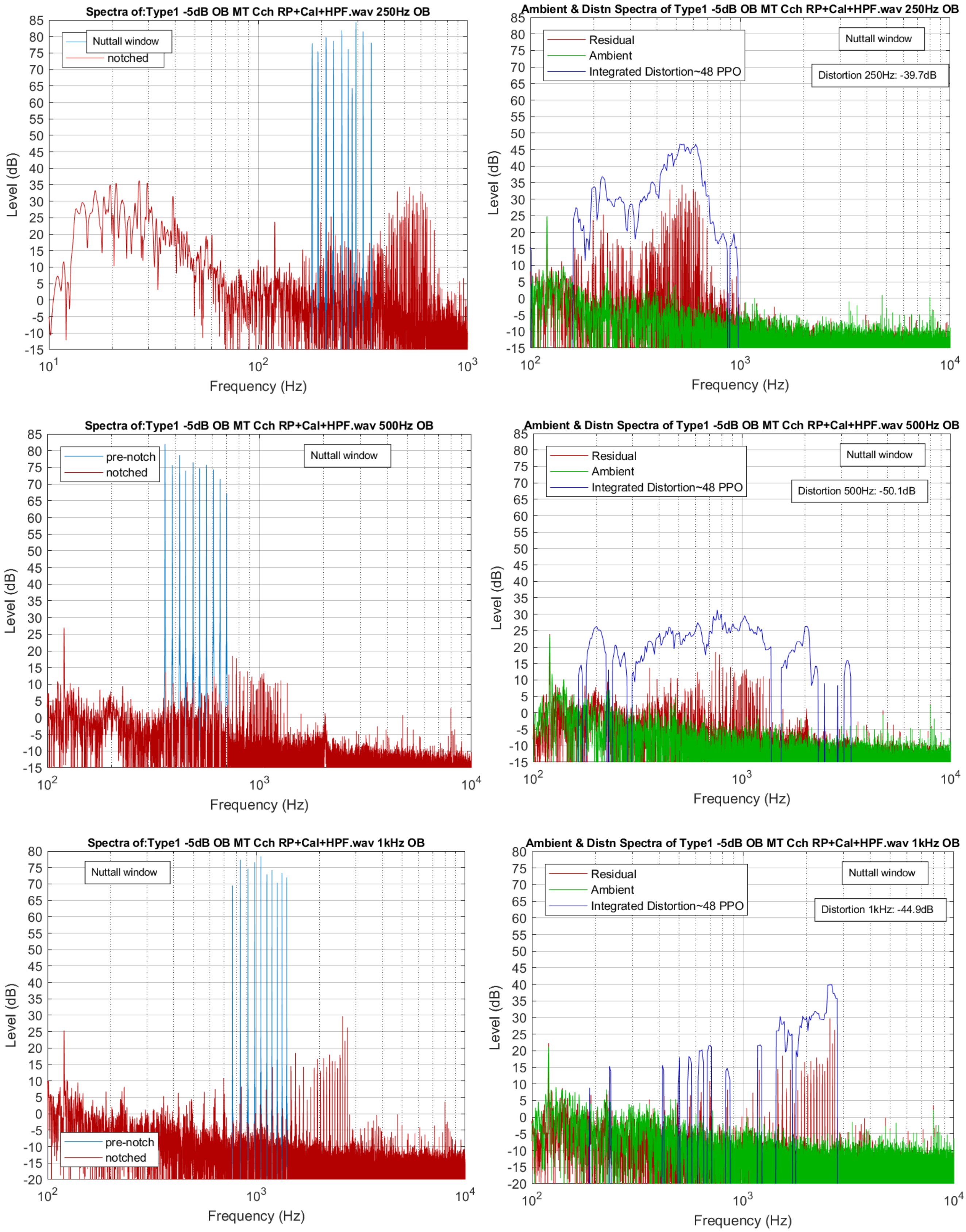


Figure 5 cont.

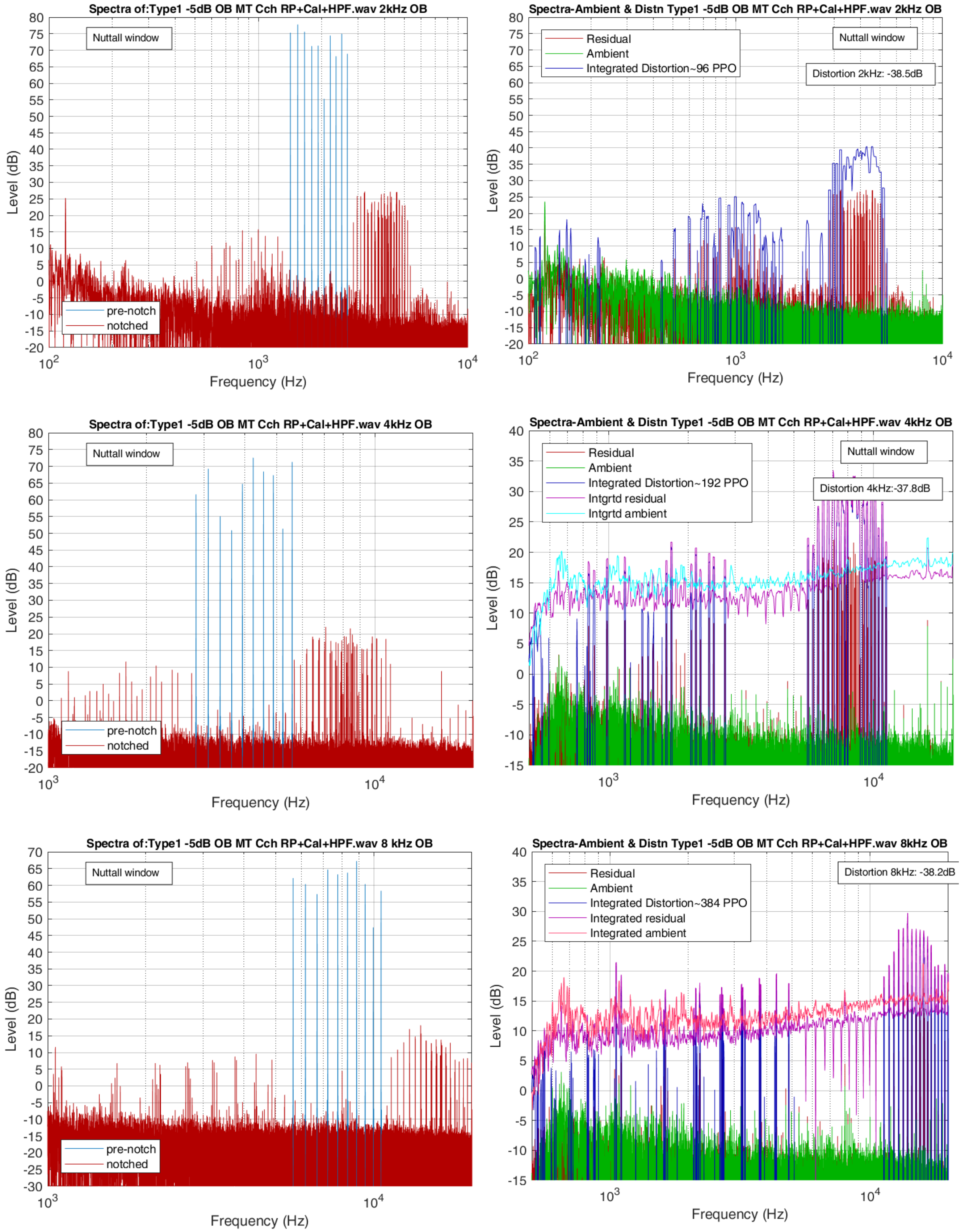


Figure 6. Octave-band spectra for the sequence with maximum level of 0 dBFS. Spectra are the received, notched, ambient, and integrated ambient and residual signals.

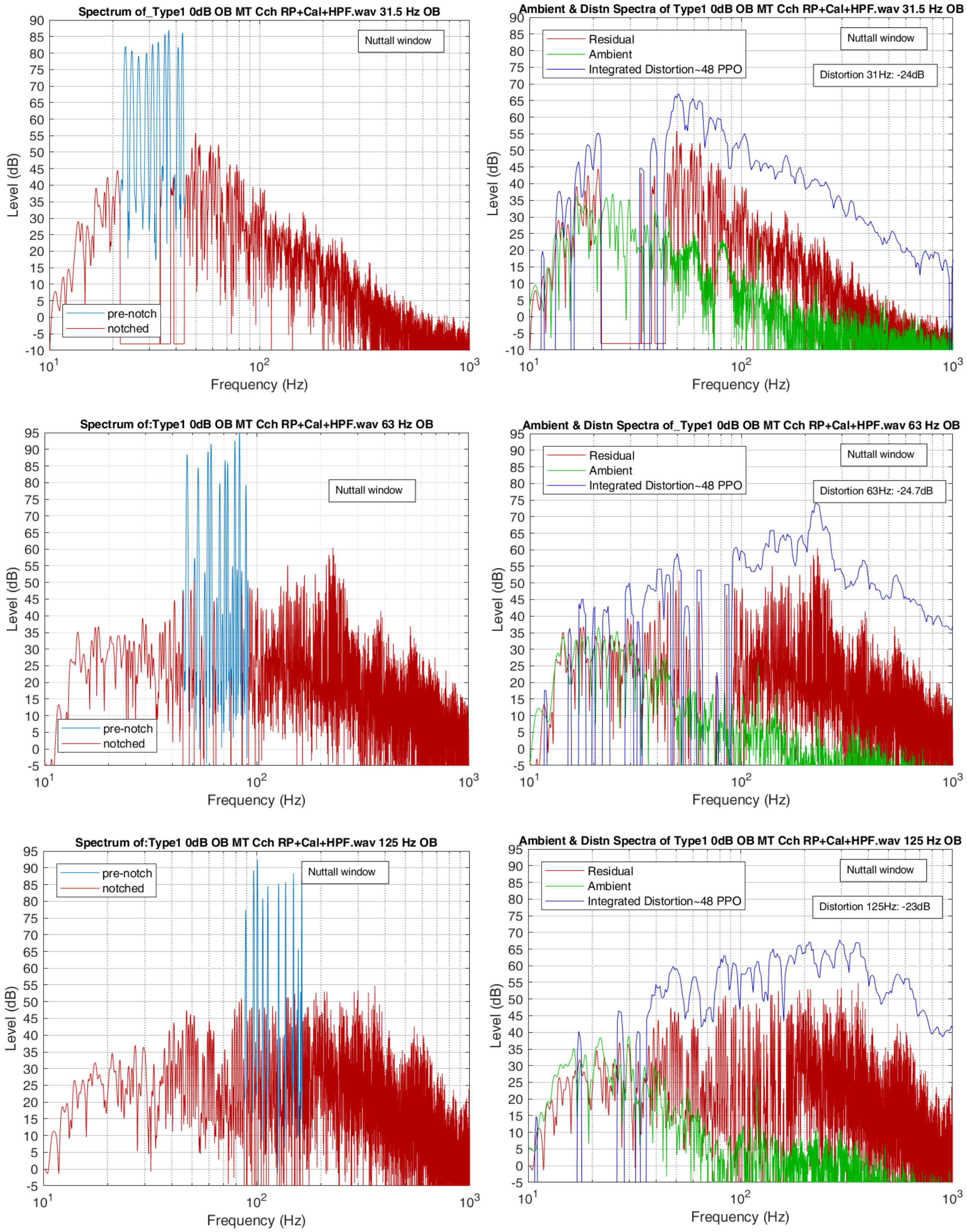


Figure 6 cont.

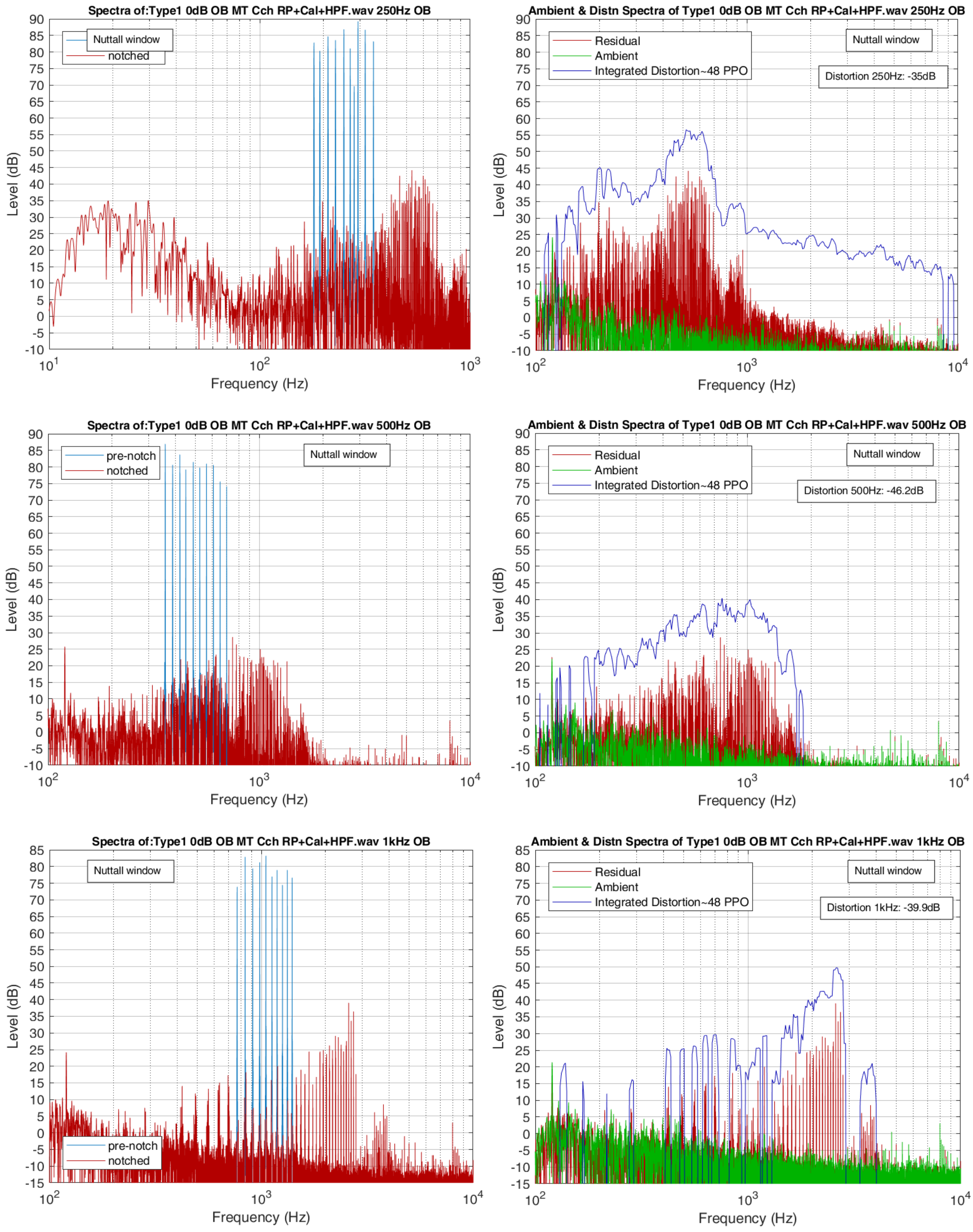
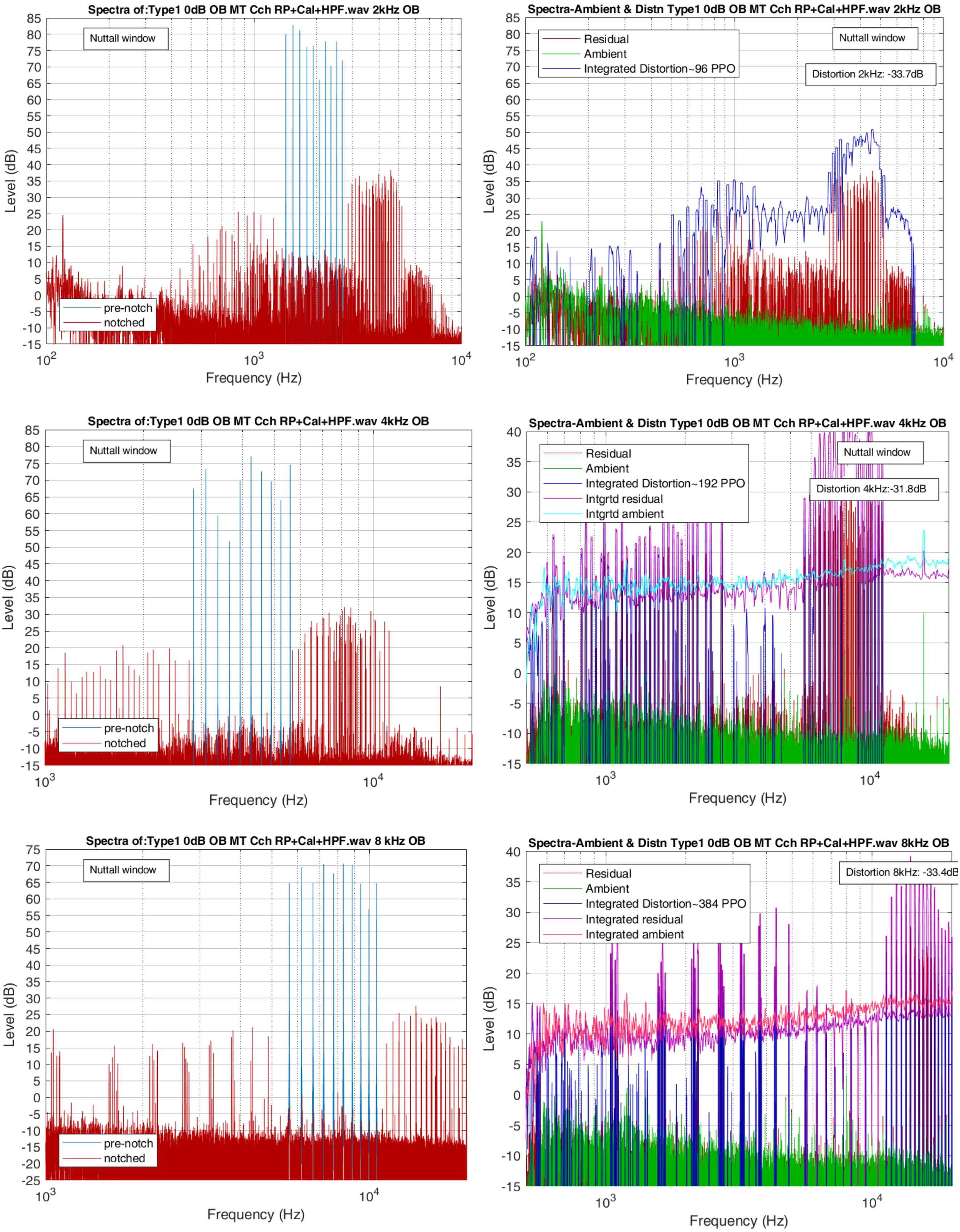


Figure 6 cont.



5 DISCUSSION AND CONCLUSION

The following observations are made:

a) The spectral distribution of the distortion products varies over the nine octave bands.

b) There is a trend commencing at 1 kHz and extending to 8 kHz, in which there are clearly defined groups of distortion products on each side of the band of tones. The 8 kHz band is unusual in that it has multiple clusters of products extending down to 1 kHz.

c) Determining the actual numerical distortion level can be hampered by the presence of ambient noise in the room, which could change between a given tone burst and the adjoining silence period. When the distortion products are substantial, the effect of the ambient noise is diminished.

d) Examination of the spectral lines of tones in the pre-notched signal (light blue traces) indicates that some tones are substantially lower than others. It is likely that destructive interference from room reflections is producing many of these frequency response aberrations.

e) If high accuracy is required, both the reflections and noise should be removed from the measurement environment, requiring the tests to be undertaken in a low-noise, anechoic space.

f) When considering how the distortion in a loudspeaker system might affect the perceived sound quality of different sections of movie soundtracks or music, the use of multiple tones in nine octave-bands may yield greater insights than wide-band multitone signals.

6 REFERENCES

[1] E. Czerwinsky, A. Voishvillo, “Multitone Testing of Sound System Components - Some Results and Conclusions, Part 1: History and Theory,” *J. Audio Eng. Soc. Vol. 49, No. 11,* Nov 2001.

[2] E. Czerwinsky, A. Voishvillo, “Multitone Testing of Sound system Components-Some results and Conclusions Part 2: Modeling and Application,” *J. Audio Eng. Soc. Vol 49, No12,* Dec 2001.

[3] S. Temme, P.Brunet, “A New Method for Measuring Distortion using a Multitone Stimulus and Non-Coherence,” in *Audio Engineering Society, 121st Convention, San Francisco*, Convention Paper 6877, 2006.

[4] A. Goertz, *Prresentation to the SMPTE 27CSS Group,* 2023.

[5] Klippel Gmbh, “Multi-Tone Distortion Measurement - Application Note,” [Online]. Available: https://www.klippel.de/fileadmin/klippel/Files/Know_How/Application_Notes/AN_16_Multi-Tone_Distortion.pdf.

[6] “LabWindows/CVI,” [Online]. Available: https://www.ni.com/docs/en-US/bundle/labwindows-cvi/page/advancedanalysisconcepts/lvac_blackman_nuttall.html.

[7] Wikipedia, “Window function,” [Online]. Available: https://en.wikipedia.org/wiki/File:Window_function_%28nuttall%29.png.