SELECTION OF NHTSA'S SOUND ANALYSIS CODE

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ABSTRACT

The Pedestrian Safety Enhancement Act of 2010 requires the National Highway Traffic Safety Administration (NHTSA) to establish a Federal Motor Vehicle Safety Standard (FMVSS 141) mandating minimum sound requirements for electric vehicles (EVs), and hybrid electric vehicles (HEVs). As part of FMVSS 141 development, NHTSA needed to select one sound analysis code (a software program) for sound data processing so that methods used to evaluate vehicle sounds for compliance testing or other purposes would be consistent. Two candidate sound analysis codes, the B&K Code and the Volpe Code, have been used by NHTSA. This paper documents NHTSA's selection of one of these two for its future use.

Criteria for selecting a sound analysis code were that the code: (1) must give correct results for mathematically-generated test cases, (2) must meet all filter requirements for one-third octave band Class 1 filters contained in ANSI S1.11-2004: Specification of Octave, Half-Octave, and Third-Octave Band Filter Sets, [1], and (3) could be made available outside the Federal government to allow others to perform sound data analyses using NHTSA's software.

The B&K and Volpe Codes both did an excellent job of calculating one-third octave band levels when pure tones were input. Both sound analysis codes correctly performed A-weighting. When a composite signal consisting of superimposed pure tones, one at the mid-band frequency of each of 13 one-third octave bands, was input, calculated levels exceeded input amplitudes by a small but acceptable amount.

The one-third octave band filters used by the B&K Code did not fully comply with one-third octave band Class 1 filter specifications contained in ANSI S1.11-2004. S1.11-2004 specifies that Class 1 filters asymptote to an attenuation of 70 dB for both high and low frequencies. For low frequencies, the B&K Code is asymptotic to between 55- and 60-dB attenuation for all one-third octave bands. For some one-third octave bands, there was also a region above the specified one-third octave pass band but below the high frequency region that also did not meet S1.11-2004 specifications. The Volpe Code filters complied with all S1.11-2004 Class 1 filter specifications for all one-third octave bands. For this, and other reasons, the Volpe code has been selected for future NHTSA analyses of vehicle-emitted sound.

Additional details about this research are contained in the NHTSA Technical Report "Selecting a Sound Analysis Code for use with NHTSA Test Procedures to Characterize Vehicle Sounds," [2].

BACKGROUND AND OBJECTIVES

As directed by Pedestrian Safety Enhancement Act of 2010, NHTSA established FMVSS 141 setting minimum sound requirements for EVs, and HEVs. (In addition to EVs and HEVs, FMVSS 141 also applies to low speed electric vehicles (LSVs).) The sounds required by FMVSS 141 are ones that pedestrians should be able to hear in a range of ambient environments and contain acoustic signal content that pedestrians should recognize as being emitted from a vehicle. FMVSS 141 will ensure that visually-impaired and other pedestrians can detect and recognize nearby HEVs, EVs, and LSVs by hearing those vehicles.

As part of its effort to develop a FMVSS 141 compliance test procedure, NHTSA measured and characterized sounds emitted by a selection of existing vehicles. NHTSA measured sounds produced by vehicles using a slightly modified version of the test methodology contained in the September 2011 version of SAE Surface Vehicle Recommended Practice J2889-1, "Measurement of Minimum Noise Emitted by Road Vehicles" [3].

After the measured vehicle sound data was recorded, each sound file was analyzed using a sound analysis code (a software program to process measured sound data). A sound analysis code calculates such quantities as Overall Sound Pressure Level (SPL) as a function of time, the Maximum and Minimum Overall SPLs during a test, one-third octave band levels as a function of time for each one-third octave band of interest, and the maximum and minimum one-third octave band levels during a test from sound data. NHTSA uses the output of a sound analysis code to characterize the sounds produced by a vehicle during a test and to determine if a vehicle complies with minimum requirements.

Two sound analysis codes[1], Brüel & Kjær's PULSE Reflex software (the "B&K Code") and a code developed by the Volpe National Transportation Systems Center (the "Volpe Code") have been used by NHTSA to analyze vehicle sound data. Sound data recorded during some test runs was analyzed using both the B&K Code and the Volpe Code. Analysts examining results from these runs noted that there were slightly different overall SPLs and one-third octave band levels for the exact same recorded sound data depending upon the sound analysis code used. While the differences that were seen were not large, they were not acceptable for a prospective NHTSA compliance test.

To resolve discrepancies in results from the B&K Code versus the Volpe Code, NHTSA undertook the work described in this paper. The objective of this research was to select one sound analysis code that NHTSA would use to process and analyze future vehicle sound data. Selection criteria for choosing one sound analysis code were:

- Must generate correct results for mathematically-generated test cases.
- Must meet all filter requirements for one-third octave band Class 1 filters that are contained in ANSI S1.11-2004 over the entire range of frequencies.

[1] Although NHTSA has not used them, there are other commercially-available sound analysis codes. The goal of this research was not to examine every available sound analysis code; instead, it was to examine the two sound analysis codes NHTSA had previous experience with and select one for future NHTSA use.

- Could be made available to other individuals or organizations that wish to perform sound data analysis using the same software used by NHTSA.

One-Third Octave Bands of Interest to NHTSA

NHTSA is focusing its FMVSS 141 compliance testing on 13 one-third octave bands having nominal mid-band frequencies ranging from 315 to 5,000 Hz. Additional details about these one-third octave bands can be found in ANSI S1.11-2004.

DESCRIPTION OF THE B&K AND VOLPE SOUND ANALYSIS CODES

The purpose of a sound analysis code, from a NHTSA perspective, is to process measured sound data to calculate Overall SPL and sound levels in the 13 one-third octave bands of interest to NHTSA. For vehicle pass-by testing or stationary vehicle sounds, the maximums during the test of these values are determined. For analysis of ambient sounds, minimums of these values are determined.

The B&K sound analysis code is commercially-available software licensed from Brüel & Kjær. The B&K Code performs A-weighting, exponential averaging, and filtering while processing sound recordings to obtain Overall SPL and the 13 one-third octave band sound levels.

The Volpe Code was developed for the United States Government by the Volpe National Transportation Systems Center. Since this sound analysis code is the property of the United States Government, it can be shared with interested parties. The Volpe Code performs A-weighting, exponential averaging, and filtering while processing sound recordings to obtain Overall SPL and the 13 one-third octave band sound levels.

TEST CASES FOR VALIDITY CHECKING

Both sound analysis codes were tested to ensure that they provide correct results. This was done through Test Cases. Test Cases were computer-generated sound pressure data files developed to test specific aspects of sound analysis codes. They were not generated through vehicle testing; they were completely artificial simulations. Once Test Cases had been developed, they were processed using both sound analysis codes.

The Test Cases NHTSA developed were sound pressure data files for which outputs expected from sound analysis codes were known in advance. To ensure that expected results from Test Cases were known *a priori*, very simple sound pressure functions (pure tones) were used. Test Case sound data files do not have the complexity of actual, measured, sound data; this is what makes it possible to determine *a priori* what the correct output from the analysis code should be.

Test Case 1: Single Frequency, Constant-Amplitude, Pure Tones

For Test Case 1, the pressure associated with a sound as a function of time was given by a single, constant-amplitude, constant-frequency, sine wave (i.e., a pure tone). Both the constant-amplitude and the constant-frequency were varied from test run to test run. Two constant-amplitudes, 40- and 60-dB, which are typical of sounds made by vehicles, were used.

The pure tones for Test Case 1 were generated at 201 individual frequencies every 1/8th of a one-third octave band (i.e., every 1/24th of a full octave) over the covered frequency range. The covered frequency range was approximately 70 Hz to 22,300 Hz. This frequency range encompasses an additional six one-third octave bands on either side of the 13 one-third octave bands of interest to NHTSA. This range was chosen to ensure a full profile of how each code responds to known inputs.

The following aspects of sound analysis code correctness were checked using Test Case 1:

- Correctness of calculated amplitudes, when A-weighting was **not** applied, for pure tones at frequencies corresponding to the exact mid-band of each of 13 one-third octave bands.
- Correctness of calculated amplitudes, when A-weighting was applied, for pure tones at frequencies corresponding to the exact mid-band of each of 13 one-third octave bands.
- The band-pass filters that split frequency weighted sound pressure level data into 13 one-third octave bands. NHTSA requires these band-pass filters to meet all filter requirements for Class 1 one-third octave band filters contained in ANSI S1.11-2004.

Test Case 2: Multiple Frequency, Constant-Amplitude, Pure Tones

For Test Case 2, the sound pressures from 13 pure tones were superimposed to form one sound pressure signal. These 13 pure tones were at the exact mid-band frequencies of each one-third octave band.

Only two variations were developed for Test Case 2. The first had a 40-dB pure tone at the exact mid-band frequency of each of the 13 one-third octave bands (giving an Overall SPL of 51.1394 dB). The second had a 60-dB pure tone at the exact mid-band frequency of each of the 13 one-third octave bands (giving an Overall SPL of 71.1394 dB).

The following aspects of sound analysis code correctness were checked using Test Case 2 data files:

- Correctness of calculated amplitudes, when A-weighting was **not** applied, for a multi-tone sound waveform.
- Correctness of calculated amplitudes, when A-weighting was applied, for a multi-tone sound waveform.

CORRECTNESS OF AMPLITUDES

Using a Single Pure Tone without A-Weighting

The first test for both sound analysis codes was correctness of their calculated one-third octave band levels for individual pure tones when A-weighting was **not** applied. This was accomplished by running 26 variations of Test Case 1, comprising two amplitudes (40-dB and 60-dB input signals) for each of 13 pure-tone frequencies, one at the exact mid-band frequency of each one-third octave band with A-weighting disabled.

To match the specifications of Table B1, “Limits on Relative Attenuation for One-Third Octave Band Filters,” in ANSI S1.11-2004, for Class 1 filters, each calculated one-third octave band level, at the exact mid-band frequency of each 13 one-third octave bands must match the nominal input level within a tolerance of ±0.30 dB.

As shown by Table 1, for both sound analysis codes, for both amplitudes of input signals, and for all 13 one-third octave bands, the calculated levels were within ±0.01 dB of the input amplitude. This was well within the ±0.30 dB tolerance permitted by ANSI S1.11-2004.

Using Multiple Tones without A-Weighting

The next thing checked was correctness of calculated amplitudes for the multi-tone sound input of Test Case 2. For Test Case 2, sound pressures from 13 pure tones were superimposed to form one sound pressure signal. Only two test runs were made using Test Case 2. The first had a 40-dB pure tone at the exact mid-band frequency of each one-third octave band. The second had a 60-dB pure tone at the exact mid-band frequency of each one-third octave band. Table 2 summarizes Test Case 2 results.

For the B&K Code, for both amplitudes of input signals, and for all 13 one-third octave bands of interest to NHTSA, calculated band levels were within (+0.04, +0.08) dB of input amplitude. For the Volpe Code, calculated band levels were within (+0.06, +0.13) dB of input amplitude.

Calculated band levels for Test Case 2 always exceeded the input amplitudes by a small amount (up to 0.13 dB). This was as expected since ANSI S1.11-2004 does not require, and neither the B&K Code nor the Volpe Code have, infinitely fast filter roll-offs at the edges of one-third octave bands. Due to finite filter roll-offs, a small amount of energy leaks through into each one-third octave band from other, nearby one-third octave bands. The 315 Hz and 5,000 Hz one-third octave bands have calculated band levels that are closer to the input amplitude than the other 11 bands. This was because, for these two bands, there were only bands containing acoustic energy on one side and not on both sides as was the case for the other 11 bands. Although ANSI S1.11-2004 does not apply to composites of pure tones, the composite multi-tone results were within the permitted ±0.30 dB pure tone tolerance.

Comparison of 40-dB and 60-dB Input Amplitude Results

Both for individual pure tones and more complex, 13 superimposed pure tones, no differences were seen between the 40-dB and 60-dB input amplitude results. Therefore, to reduce the number of analyses that had to be performed, the remainder of this paper will be based only on results from 40-dB input amplitude test cases.

Using a Single Pure Tone with A-Weighting

The correctness of calculated amplitudes when A-weighting was applied was checked for both sound codes both when a single pure tone was input (Test Case 1) and when a composite signal composed of multiple pure tones was input (Test Case 2).

To check correctness of A-weighting when a single pure tone was input, 13 Test Case 1 runs were made. A single 40-dB amplitude pure tone was input at the exact mid-band frequency of each of 13 one-third octave bands.

Table 3 shows calculated, A-weighted, band levels and the effects of A-weighting for both sound analysis codes for all 13 one-third octave bands. Table 3 also shows the theoretical effects of applying A-weighting. For both the B&K and Volpe Codes, the actual effects of A-weighting were very close to the theoretical effects. For the B&K Code, there was a maximum difference between the actual and theoretical effects of A-weighting of 0.05 dB at 5,000 Hz. For the Volpe Code, there was a maximum difference between the actual and theoretical effects of A-weighting of 0.05 dB at 4,000 Hz.

Using Multiple Tones with A-Weighting

To check the correctness of A-weighting when multiple pure tones were simultaneously input, one Test Case 2 run was made. Multiple 40-dB amplitude pure tones were input at the exact mid-band frequency of each of 13 one-third octave bands.

The Table 4 shows calculated band levels after applying A-weighting and differences due to A-weighting for both sound analysis codes for all 13 one-third octave bands. For both the B&K and Volpe Codes, the actual effects of A-weighting were very close to the theoretical effects. For the B&K Code, there was a maximum difference between the actual and theoretical effects of A-weighting of 0.05 dB at 5,000 Hz. For the Volpe Code, there was a maximum difference between actual and theoretical effects of A-weighting of 0.05 dB at 4,000 Hz.

COMPARISONS TO ANSI S1.11-204 CLASS 1 FILTER SPECIFICATIONS

SAE J2889-1, specifies that "the corresponding 1/3 octave results per ANSI S1.11, Class 1"[2] shall be reported. ANSI S1.11-2004: "Specification of Octave, Half-Octave, and Third-Octave Band Filter Sets," contains specifications for Class 1 filters. For its work, NHTSA is using the base-ten system for calculating frequencies. The base-ten system has been chosen because ANSI S1.11-2004 states that while the base-two system for determining frequencies is acceptable, the "base-ten system is preferred."[3]

In the figure that follows, linear interpolation between data points in ANSI S.1.11-204 were used to develop the Minimum and Maximum Attenuation Limit lines shown.

All 201 Test Case 1 single-frequency, constant (40-dB) amplitude pure tones were processed using both sound analysis codes. A-weighting was **not** used for these runs. Results were used to check correctness of filters used by the B&K and Volpe Codes to calculate one-third octave bands.

Figure 1 shows performance of the B&K Code's and Volpe Code's filters for a typical one-third octave band, the 1,000 Hz band, over the entire frequency range from 80 to 20,000 Hz. For a filter to comply with the ANSI S1.11-2004 Class 1 filter specifications, its attenuation must fall between the "Minimum Attenuation Limit" and the "Maximum Attenuation Limit" curves over the entire frequency range.

As shown by Figure 1, the filters used by the B&K Code did not comply with Class 1 filter specifications contained in ANSI S1.11-2004 over the entire frequency range. Note: In documentation for the B&K Code, B&K does not claim that their filters meet the Class 1 filter specifications contained in ANSI S1.11-2004. B&K states "Fulfills ICE225-1966, DIN45651, and ANSI S1.11-1986, Order 3, Type 1-D" filter specifications.

For frequencies around the pass band, the B&K Code filters complied with the Class 1 filter specifications contained in ANSI S1.11-2004. For low frequencies, the B&K Code filters were asymptotic to an attenuation of 55- to 60-dB while ANSI S1.11-2004 Class 1 specifications require an asymptotic attenuation of at least 70 dB. The B&K Code filters were closer to ANSI S1.11-2004 Class 1 filter specifications in frequencies substantially above the pass band. The asymptotic behavior of the B&K Code filters for high frequencies met the ANSI S1.11-2004 Class 1 filter specified attenuation of 70 dB. However, for the 1,600 Hz and lower frequency one-third octave bands, there is a mid-frequency region between the pass band and the high frequency range for which B&K Code filters did not meet ANSI S1.11-2004 filter specifications.

The filters used by the Volpe Code complied with Class 1 filter specifications contained in ANSI S1.11-2004. For frequencies around the pass band, the Volpe Code filters fully comply with pass band

[2] Quote from SAE J2889-1.
[3] Quote from Section 3.2 of ANSI S1.11-2004.

Class 1 filter specifications contained in ANSI S1.11-2004 for all 13 one-third octave bands. For frequencies substantially above or below the pass band, its attenuations substantially exceeded the minimum 70 dB filter attenuation specified in ANSI S1.11-2004.

CONCLUSIONS

Both the B&K and Volpe Codes did an excellent job of calculating one-third octave band levels when one or more pure tones were input at the exact mid-band frequencies of the 13 one-third octave bands. Calculated band levels were well within the ±0.30 dB tolerance permitted by ANSI S1.11-2004.

A-weighting is correctly performed by both the B&K and Volpe Codes.

One of the objectives of this work was to select one sound analysis code that met all of the filter requirements for one-third octave band Class 1 filters that are contained in the standard ANSI S1.11-2004 for future use by NHTSA. The one-third octave band filters used by the B&K Code did not fully comply with one-third octave band Class 1 filter specifications contained in ANSI S1.11-2004. The Volpe Code filters complied with all S1.11-2004 Class 1 filter specifications for all one-third octave bands. For this, and other reasons, the Volpe code has been selected for future NHTSA analyses of vehicle-emitted sound.

NHTSA will be making an executable image (so that parties without a MATLAB license can still run the Volpe Code if they wish) of the Volpe Code available to interested parties. The Volpe National Transportation Systems Center is currently adding an easy-to-use graphical user interface to the Volpe Code. The Volpe Code with the graphical user interface will not only calculate overall sound pressure levels and one-third octave band levels for a set of measured vehicle sound data but will also determine whether the vehicle complies with the sound requirements contained in the final version of FMVSS 141. When completed and tested, this software will either be placed in the appropriate docket at www.regulations.gov and/or made accessible on the NHTSA website.

REFERENCES

1. ANSI S1.11-2004: “Specification of Octave, Half-Octave, and Third-Octave Band Filter Sets”
2. Garrott, W. R., Hoover, R.L., Gerdus, E., and Rao, S., “Selecting a Sound Analysis Code for use with NHTSA Test Procedures to Characterize Vehicle Sounds,” NHTSA Technical Report DOT HS 812 284, June 2016
3. SAE Surface Vehicle Standard J2889-1, “Measurement of Minimum Noise Emitted by Road Vehicles”

Table 1: Calculated Band Levels for 40- and 60-dB Input Signals without A-Weighting for Test Case 1

Nominal One-Third Octave Midband Frequency (Hz)	40-dB Input Signal				60-dB Input Signal			
	B&K Code		Volpe Code		B&K Code		Volpe Code	
	Calculated Band Level (dB)	Difference from 40-dB (dB)	Calculated Band Level (dB)	Difference from 40-dB (dB)	Calculated Band Level (dB)	Difference from 40-dB (dB)	Calculated Band Level (dB)	Difference from 40-dB (dB)
315	40.01	+0.01	40.01	+0.01	60.01	+0.01	60.01	+0.01
400	40.01	+0.01	40.01	+0.01	60.01	+0.01	60.01	+0.01
500	40.00	0.00	40.00	0.00	60.00	0.00	60.00	0.00
630	40.00	0.00	40.00	0.00	60.00	0.00	60.00	0.00
800	40.00	0.00	40.00	0.00	60.00	0.00	60.00	0.00
1,000	39.99	-0.01	40.00	0.00	59.99	-0.01	60.00	0.00
1,250	40.00	0.00	40.00	0.00	60.00	0.00	60.00	0.00
1,600	40.00	0.00	40.00	0.00	60.00	0.00	60.00	0.00
2,000	40.00	0.00	40.00	0.00	60.00	0.00	60.00	0.00
2,500	39.99	-0.01	40.00	0.00	59.99	-0.01	60.00	0.00
3,150	40.00	0.00	40.00	0.00	60.00	0.00	60.00	0.00
4,000	40.01	+0.01	40.00	0.00	60.01	+0.01	60.00	0.00
5,000	40.01	+0.01	40.00	0.00	60.01	+0.01	60.00	0.00

Table 2: Calculated Band Levels for 40- and 60-dB Input Signals without A-Weighting for Test Case 2

Nominal One-Third Octave Midband Frequency (Hz)	40-dB Input Signal				60-dB Input Signal			
	B&K Code		Volpe Code		B&K Code		Volpe Code	
	Calculated Band Level (dB)	Difference from 40-dB (dB)	Calculated Band Level (dB)	Difference from 40-dB (dB)	Calculated Band Level (dB)	Difference from 40-dB (dB)	Calculated Band Level (dB)	Difference from 40-dB (dB)
315	40.04	+0.04	40.06	+0.06	60.04	+0.04	60.06	+0.06
400	40.07	+0.07	40.11	+0.11	60.07	+0.07	60.11	+0.11
500	40.07	+0.07	40.13	+0.13	60.07	+0.07	60.13	+0.13
630	40.06	+0.06	40.13	+0.13	60.06	+0.06	60.13	+0.13
800	40.06	+0.06	40.13	+0.13	60.06	+0.06	60.13	+0.13
1,000	40.05	+0.05	40.13	+0.13	60.05	+0.05	60.13	+0.13
1,250	40.05	+0.05	40.13	+0.13	60.05	+0.05	60.13	+0.13
1,600	40.07	+0.07	40.12	+0.12	60.07	+0.07	60.12	+0.12
2,000	40.07	+0.07	40.12	+0.12	60.07	+0.07	60.12	+0.12
2,500	40.05	+0.05	40.13	+0.13	60.05	+0.05	60.13	+0.13
3,150	40.06	+0.06	40.13	+0.13	60.06	+0.06	60.13	+0.13
4,000	40.08	+0.08	40.12	+0.12	60.08	+0.08	60.12	+0.12
5,000	40.04	+0.04	40.06	+0.06	60.04	+0.04	60.06	+0.06

Table 3: A-Weighted Calculated Band Levels for 40-dB Input Signals for Test Case 1

Nominal One-Third Octave Midband Frequency (Hz)	Exact A-Weighting Correction (dB)	B & K Code		Volpe Code	
		Calculated Band Level (dB)	A-weighting Effect (dB)	Calculated Band Level (dB)	A-Weighting Effect (dB)
315	-6.60	33.40	-6.60	33.40	-6.61
400	-4.80	35.20	-4.80	35.20	-4.81
500	-3.20	36.78	-3.23	36.77	-3.23
630	-1.90	38.10	-1.90	38.10	-1.90
800	-0.80	39.17	-0.82	39.18	-0.82
1,000	0.00	39.99	0.00	40.00	0.00
1,250	0.60	40.59	0.59	40.59	0.59
1,600	1.00	40.98	0.98	40.98	0.98
2,000	1.20	41.20	1.20	41.20	1.20
2,500	1.30	41.26	1.27	41.27	1.27
3,150	1.20	41.19	1.20	41.19	1.19
4,000	1.00	40.98	0.97	40.95	0.95
5,000	0.50	40.55	0.55	40.50	0.50

Table 4: A-Weighted Calculated Band Levels for 40-dB Input Signals for Test Case 2

Nominal One-Third Octave Midband Frequency (Hz)	Exact A-Weighting Correction (dB)	B & K Code		Volpe Code	
		Calculated Band Level (dB)	Effect of A-weighting (dB)	Calculated Band Level (dB)	Effect of A-weighting (dB)
315	-6.60	33.45	-6.59	33.47	-6.59
400	-4.80	35.27	-4.80	35.34	-4.77
500	-3.20	36.84	-3.23	36.91	-3.22
630	-1.90	38.16	-1.90	38.23	-1.90
800	-0.80	39.24	-0.82	39.30	-0.83
1,000	0.00	40.06	0.00	40.13	0.00
1,250	0.60	40.65	0.59	40.72	0.60
1,600	1.00	41.05	0.98	41.11	0.99
2,000	1.20	41.27	1.20	41.32	1.20
2,500	1.30	41.32	1.27	41.40	1.27
3,150	1.20	41.26	1.20	41.32	1.19
4,000	1.00	41.04	0.97	41.08	0.95
5,000	0.50	40.59	0.55	40.58	0.51

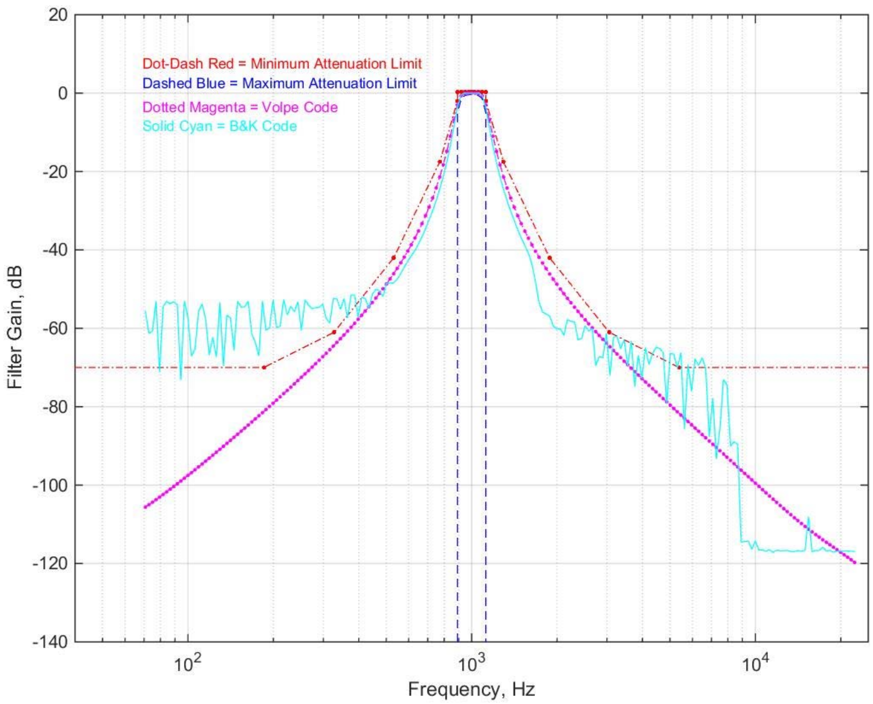

Figure 1: Filter Performance for the 1,000 Hz One-Third Octave Band