A CRITICAL ANALYSIS OF LOUDNESS CALCULATION METHODS

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1. INTRODUCTION

Loudness aims to quantify how loud a sound is perceived to be in comparison to a standard sound [1]. It accounts for both the frequency-sensitivity of the ear and masking effects. The loudness of a sound is most commonly computed from 1/3 octave band sound pressure levels measurements of the source. However, the calculation procedure is poorly understood despite having been standardised in ISO 532B (1975) and DIN 45631 (1991). There exist commercial software packages to determine loudness. In this paper, the 01dB software packages dBFA and dBSonic were considered. For this investigation, four noise sources are used in comparing the software packages to a public domain code and two codes written by the present authors – one based on ISO 532B, the other on DIN 45631. A 1-kHz tone, pink noise, a six-cylinder spark-ignition engine and a six-cylinder diesel engine were used. The purpose of this comparison is to evaluate the validity of the results obtained, as well as to gain insight into the shortcomings of the relevant standards. In addition, comparisons of results amongst the different sound types will serve to illustrate the differences between sound pressure level (SPL) and loudness.

2. THE DEFINITION OF LOUDNESS

In general, a sound will prevent other sounds of lower sound pressure level but with similar frequency content from being heard. This is known as masking. Typically, sound level meters and frequency analysers will present the frequency content of a measured signal in terms of fractional octave bands. The human hearing system does not use fractional octave band filtering: the major range of human hearing is more properly divided into 24 "critical bands" based on the frequency ranges in which masking will occur – that is, if two sounds occur with frequency content within one band of each other, masking will take place [1]. The critical band representation of a sound is its *excitation* [1] – some excitation occurs outside of the critical band in which the sound occurs. So, "similar" frequency content means that one sound's critical-band spectrum is overshadowed by the masking sound's critical-band spectrum. Loudness is "the sensation that corresponds most closely to the sound intensity of the stimulus" [1]. The loudness of a 1-kHz tone at an SPL of 40 dB is 1 sone. The concept of "specific loudness" is employed to mean the contribution to the total loudness of a specific slice of the critical band spectrum. Critical-band filtering is not widely available, so a procedure was developed for use with 1/3 octave band data [1, 4]. Determining the actual loudness of a sound involves several steps. The procedure is a graphical one, standardised in ISO 532 B [2] and DIN 45631 [3]. It is somewhat tedious to use and so two computer programs were written to automate it. One was written by Paulus and Zwicker [4, 5]. The other was developed as part of DIN 45631 [3, 6]. The calculation process is outlined in [4].

3. SOUNDS TESTED AND PROCESSING SYSTEMS USED

A comparison of the results for loudness computed from various methods was investigated in this study. Two basic sources of input data were available: a sound level meter (SLM) and a 01 dB data acquisition system (DAQ). The SLM directly gives 1/3 octave band levels while the data from the DAQ can be filtered to give them. This process was accomplished in several ways. The 01dB software dBFA filters according to EIC 1260. The 01dB software dBSonic uses an unknown filtering algorithm. The MATLAB program [7], uses ANSI S1.11. Five processing methods were used for this study. These were: a Visual Basic (VB) program adapted from [5], a VB program adapted from [6], dBFA, dBSonic, and a MATLAB program [7] based on [6]. The two VB programs were adapted by the present authors. In order to efficiently compare the processing methods and input data, eight combinations were developed, listed in Table 1. For the 1-kHz tone, combinations 1 & 3 were not considered because of SLM hardware limitations.

4. RESULTS AND DISCUSSION

The loudness results for the four types of sounds are shown in table 2. For the 40 dB tones, only the Excel (ISO) method using EIC 1/3 octave data from dBFA, dBSonic, and the Hastings (DIN) method using ANSI 1/3 octave data give the correct result of exactly 1 sone_{GF}. For the 80 dB tones, no combination gives exactly 16 sone, which is the theoretical loudness for this sound. However, dBFA, dBSonic and Hastings with ANSI filtering give results closest to the theoretical value: 16.7, 16.5 and 16.4 sone_{GF} respectively. Only dBSonic and DIN with ANSI filtering give consistently accurate loudness values for the tones. Based on the results from the tones, dBSonic and DIN with ANSI filtering will be taken as "correct" values of loudness.

Table 1: Combinations used

Com-bination	Input Data	Processing Method
1	SLM 1/3 oct.	VB from [4, 5] (ISO)
2	dbFA 1/3 oct. (EIC)	VB from [4, 5] (ISO)
3	SLM 1/3 oct.	VB from [6] (DIN)
4	dbFA 1/3 oct. (EIC)	VB from [6] (DIN)
5	dBFA 1/3 oct. (EIC)	dBFA
6	dBSonic 1/3 oct.	dBSonic
7	MATLAB 1/3 oct. (ANSI)	MATLAB (DIN)
8	dbFA 1/3 oct. (EIC)	MATLAB (DIN)

By looking at the results of the DIN loudness calculations using 1/3 octave data filtered via EIC 1260, ANSI S1.11, or using the SLM, it becomes apparent that there is more than just the calculation routine that affects the value obtained: the filtering method plays a significant. There is no mention of the method whereby the 1/3 octave band levels used should be acquired in ISO 532 B [2], nor in the numerical methods described in [4], [5] and [6]. This is a significant oversight in the specification of these standards.

All the sounds gave an A-weighted SPL of 80 dBA, while the loudness values for these sounds are highly varied: the pink noise has a loudness about three times that of the 1-kHz tone! It is also interesting to compare results for ISO and DIN given the same 1/3 octave band inputs. The error varies from 2.63% to 7.95%. Finally, it may not be meaningful to report loudness values with great precision. Consider the 80 dB tone. With an SPL of 80 dB, the loudness is about 16.5 sone$_{GF}$. According to the power law described in [1], a just-perceptible change to 83 dB would result in a new loudness of 19.7 sone$_{GF}$. This is a change of 3.7 sone! So, here the practical accuracy limit would be a range of this magnitude, ±1.8 sone.

5. CONCLUSIONS

The physical meaning of and calculation procedures for determining loudness were reviewed. 1-kHz tones at 40 and 80 dB(A), and pink noise, gasoline and diesel engine idle noise at 80 dBA were used to compare eight combinations of loudness calculation methods and 1/3 octave band filtering techniques. It was determined that the only two combinations to give accurate results were dBSonic and DIN with ANSI filtering methods. The program based on ISO does not seem to be accurate. The calculation of loudness from 1/3 octaves cannot be separated from the filtering process, as different methods all result in different values even when processed using a single calculation method. This dependence is largely ignored in the literature [1, 2, 4, 5, 6]. The results also highlight the difference between SPL and loudness. While all the sounds tested had an SPL of 80 dBA, their loudness varied from 16.5 to 50.1 sone$_{GF}$. Finally, when dealing with loudness, the error will be in the range of ±1.8 sone.

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Table 2: Measurement results (sone$_{GF}$)

Combination	Pink Noise 1	Pink Noise 2	Diesel 1	Diesel 2	Diesel 3	Gaso-line 1	Gaso-line 2	Gaso-line 3	Tone 40 dB 1	Tone 40 dB 2	Tone 80 dB 1	Tone 80 dB 2
1	54.9	54.0	24.0	24.0	23.9	27.5	27.2	26.5				
2	52.6	51.8	24.0	23.8	23.8	27.0	26.3	25.7	1.0	1.0	14.8	14.8
3	53.5	52.5	22.7	22.5	22.4	26.2	25.9	25.2				
4	51.1	50.3	22.7	22.4	22.5	25.8	25.3	24.5	0.9	0.9	14.3	14.3
5	54.0	53.1	24.5	24.2	24.2	27.7	27.0	26.2	1.1	1.1	16.7	16.7
6	50.8	49.9	22.2	22.0	22.1	25.3	24.7	24.0	1.0	1.0	16.5	16.5
7	50.4	49.4	22.4	22.1	22.1	25.3	24.8	24.2	1.0	1.0	16.4	16.4
8	51.1	50.3	22.7	22.4	22.5	25.8	25.3	24.5	0.9	0.9	14.3	14.3