A Critical Analysis of Loudness Calculation Methods

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ABSTRACT

The physical meaning and methods of determining loudness were reviewed. Loudness is a psychoacoustic metric which closely corresponds to the perceived intensity of a sound stimulus. It can be determined by graphical procedures, numerical methods, or by commercial software. These methods typically require the consideration of the 1/3 octave band spectrum of the sound of interest. The sounds considered in this paper are a 1 kHz tone and pink noise. The loudness of these sounds was calculated in eight ways using different combinations of input data and calculation methods. All the methods considered are based on Zwicker loudness. It was determined that, of the combinations considered, only the commercial software dBSonic and the loudness calculation procedure detailed in DIN 45631 using 1/3 octave band levels filtered using ANSI S1.11-1986 gave the correct values of loudness for a 1 kHz tone. Comparing the results between the sources also demonstrated the difference between sound pressure level and loudness. It was apparent that the calculation and filtering methods must be considered together, as a given calculation will produce different results for different 1/3 octave band input. In the literature reviewed, no reference provided a guide to the selection of the type of filtering that should be used in conjunction with the loudness computation method.

SOMMAIRE

La signification physique et les méthodes de déterminer la sonie ont été examinées. La sonie est une mesure psychoacoustique qui correspond étroitement à l'intensité perçue d'un stimulus sonore. Elle peut être déterminée par procédure graphique, par des méthodes numériques, ou par des logiciels commerciaux. Toutes ces méthodes exigent la considération du spectre de tiers d'octave du son d'intérêt. Les sons considérés en cet article sont un ton de 1-kHz et un bruit rose. La sonie de ces sons a été calculée de huit manières, en utilisant des différentes combinaisons des données d'entrée et des méthodes de calcul. Toutes les méthodes considérées sont basé sur la sonie Zwicker. On a déterminé que seulement le logiciel commercial dBSonic et le procédé de calcul de la sonie dans le standard allemand DIN 45631 utilisant la filtration de tiers d'octaves d'ANSI S1.11-1986 donnent les valeurs correctes de la sonie basées sur les valeurs théoriques pour les tons de 1-kHz. Comparant les résultats pour les différents bruits démontrent également la différence entre le niveau de pression acoustique et la sonie d'un bruit. Il est évident que la méthode de calcul ne puisse pas être séparée de la méthode de filtrage, car un calcul donné produira différents résultats pour des tiers d'octaves différents. Aucune mention n'est faite dans la littérature examinée de quel type de filtrage devrait être employé pour les calculs de la sonie.

1. INTRODUCTION

As the field of acoustics moves closer to the forefront of engineering, particularly in product development, it is becoming increasingly apparent that the sound pressure level (SPL) of a noise source is not the only important metric. Of equal, if not more importance, is the sound quality, or psychoacoustic characteristics of a noise source. The study of psychoacoustics involves the quantification of the human perception of sound. Psychoacoustics began in earnest with the study of correlations between acoustic stimuli and the sense of hearing in the 1930s [1], and had attracted serious attention by the 1950s [2].

One of the most commonly used psychoacoustic metrics is loudness. This metric aims to quantify how loud a sound is perceived to be in comparison to a standard sound [2]. It accounts for both frequency-sensitivity and masking effects. The loudness of a sound is most commonly computed from whole or 1/3 octave band sound pressure levels measurements of the sound source of interest. However, the calculation procedure is non-trivial and poorly understood despite having been standardized in ISO 532 (1975) [3], DIN 45631 (1991) [4], ANSI S3.4-1980 [5] (outdated), and ANSI S3.4-2005 [6]. ISO 532A defines a procedure for determining loudness based on octave band measurements of a sound source, from Stevens' method [7]; ANSI S3.4-1980 is also based on Stevens' work. ISO 532B and DIN 45631 require 1/3 octave band inputs and are based on Zwicker's method [2, 8]. The updated ANSI S3.4-2005 is based on Moore's method [9] and is not considered in this paper; nor are the standards based on Stevens' work. Only Zwicker methods are considered. There are commercial software packages that calculate loudness, some according to ISO 532B and some using non-standard methods. In this paper, the 01dB software packages dBFA and dBSonic were considered. For this investigation, two noise sources are used in comparing the software packages to a public domain code and two codes written by the authors – one based on ISO 532B, the other on DIN 45631. A 1 kHz tone and pink noise were used. The purpose of this comparison is to evaluate the validity of the results obtained from the various methods, 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 the well-accepted metric of sound pressure level and loudness.

Before a complete definition of loudness can be presented, further details need be provided on the concept of masking and on the frequency characteristics of the human hearing system. In general, a sound will prevent other sounds of lower sound pressure level but with similar frequency content from being heard. Another type of masking can occur when one sound follows very closely after another in time. The second sound may at times not be heard. This is known as temporal masking. Typically, sound level meters and frequency analyzers will present the frequency content of a measured signal in terms of fractional octave bands. Whole, 1/3, 1/12 and 1/48 octave band filters are commonly encountered. Unfortunately, the human hearing system does not use fractional octave band filtering. The major range of human hearing (20 Hz to 16 kHz) is more properly filtered into 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 [2]. These bands can be related to positions along the basilar membrane in the cochlea [10]. This band system was first proposed by Fletcher [1], and later refined by Zwicker [11], terming the divisions "critical bands" and assigned to them the units of Bark, in honor of Barkhausen (inventor of the loudness level unit "phon"). The critical bands are not of uniform width. For frequencies below 500 Hz, the bands are approximately 100 Hz wide [2, 11]. This includes the approximation that the first band begins at 0 Hz instead of the human hearing threshold of 20 Hz. Above 500 Hz, the bandwidth is approximately 20% of the centre frequency. The conversions from the critical band rate (z) to frequency (f) can be found in references [2] and [11]; analytical approximations to the critical bands exist and are also given in references [2] and [12]. Moore's work [9] re-examined the concept of the critical band and came up with a set of ERB (equivalent rectangular bandwidth) filters. These filters are similar to critical band filters at frequencies above 500 Hz, but below this they differ in that the ERB filters continue to narrow with decreasing centre frequency. Comparisons of results obtained using the Moore and Zwicker models show increased accuracy for sounds with significant low-frequency content for Moore's model [9]. Therefore, the calculation methods considered in this paper should not be used for sounds with dominant low-frequency content.

Excitation is the representation of the effect of a sound occurring within a specific critical band [2] – 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 (at least partially) overshadowed by the masking sound's critical-band spectrum. This is illustrated schematically in figure 1. Loudness is "the sensation that corresponds most closely to the sound intensity of the stimulus" [2, p. 205]. The loudness of a 1 kHz tone at an SPL of 40 dB is 1 sone. This sound is termed the reference sound. All other loudness values are in comparison to the reference. The loudness of a sound is dependant on the sound's frequency content and bandwidth. Thus, a weighting scheme such as the A-weighting scale is too simplistic to accurately determine the loudness of a sound [2, 13]. In fact, SPL as reported in dB or dBA can actually be misleading regarding the perceived loudness of a sound, as will be shown later. Because of the sloped tails on the critical-band filters in the human ear, as shown from the excitation pattern in figure 1, the proximity (in terms of frequency) of two sounds affects the total perceived loudness. In essence, unless two sounds are distantly separated in frequency, the total loudness will not be the sum of the sounds' individual loudnesses [8]. The concept of "specific loudness" is employed to mean the contribution to the total loudness of a specific slice of the critical band spectrum. Mathematically speaking,

$$N = \int_0^{24Bark} N' \cdot dz \tag{1}$$

where N is the total loudness and N' is the specific loudness in critical bandwidth dz.

Critical-band filtering is not widely available in most software, and so a procedure was developed for use with 1/3 octave band data [2, 8]. The true loudness of a sound accounts for both frequency and time masking; however, since octave band filtering requires the sound to be recorded over a finite time span, the procedure assumes a steady-state sound and thus accounts only for frequency masking. Only stationary signals are considered in this paper.

2. CALCULATION PROCEDURES

Both the graphical and numerical calculation procedures for loudness are described below.

2.1 Calculation Procedure - Graphical

Determining the actual loudness of a sound involves a number of steps: conversion of the data from 1/3 octave bands to approximated critical bands, determination of specific loudness, and then the summation to get the total loudness.
The procedure is a graphical one, standardized in ISO 532 B [3]. It is also included in DIN 45631 [4], which additionally

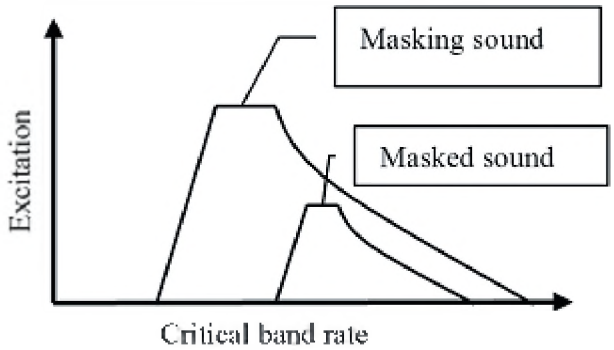

Figure 1. Schematic of masking from excitation patterns.

contains the code for a computer program to calculate loudness based on its 1/3 octave data. A simplification that is included in the procedure is the approximation of the lower slopes of excitation patterns as being infinitely steep, which is justified since they are much steeper than the upper slopes (see Figure 1) [8]. The procedure can account for sounds measured in both free and diffuse fields [3, 7].

The first step, converting 1/3 octave data to critical band data, requires that all bands up to 90 Hz be combined into the first critical band, that the three bands from 90 to 180 Hz be combined into the second critical band, and that the two bands from 180 to 280 Hz be combined into the third critical band. Above 280 Hz, the 1/3 octave bands approximately correspond to critical bands [2, 3, 7]. The levels in each critical band are then plotted on graphs (provided as part of the standard) as horizontal lines within the appropriate band at the given level [3].

The second major step, determining the specific loudness across the critical band rate scale, involves joining the horizontal lines drawn in step one in a specific way. Moving from the low to high frequency, the following rule is applied [3]: if the level in a band is higher than that of the previous band, the horizontal segments are to be joined by a vertical line. This is the infinitely-steep lower slope approximation mentioned earlier. If the level in a band is lower than that of the previous band, the reduction is not immediate but follows a curve of the type shown in Figure 2 until it intersects another of the drawn horizontal lines. This gives the Ns = f(z) curve, the area under which is the total loudness [3].

The third step, summation or integration, is simply the determination of this area by any appropriate graphical means.

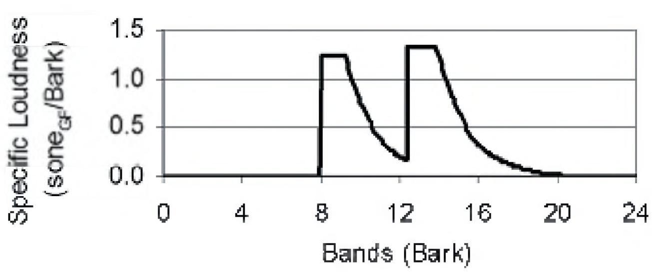

Figure 3. Sample graph (specific loudness curve).

It is to be noted that the loudness obtained is to be given in units of soneG as opposed to sone, where the G indicates that the loudness was determined graphically rather than by jury testing [2].

2.2. Calculation Procedure - Numerical

The graphical procedure described above is somewhat tedious to use in practice, and has some inherent loss in accuracy due to the interpolations required by the user. Two computer programs were written to automate this procedure. One was written by Paulus and Zwicker [8] for FORTRAN and later updated in reference [14] to run in BASIC. The other was developed as part of DIN 45631 (for BASIC) and was published in a slightly different programming format in reference [15].

2.2.1 Method 1: from references [8] and [14]

In the development of the program found in reference [8], the authors strive for improved accuracy compared to the graphical procedure by basing the program not purely on the graphs in ISO 532 B, but rather on an understanding of the underlying phenomena. As in the graphical procedure, the overall idea is to convert 1/3 octave band levels into a specific loudness curve and then integrate this curve from 0 to 24 Bark to get the total loudness. The equations and values used are empirically derived [8] and this requires the use of lookup tables for data rather than the use of functions. The calculation process is outlined below.

Consider first a simple case. For a sound with a main excitation lying within one critical band, the specific loudness is determined from [8]

$$N' = 0.064 \cdot 10^{0.025 L_{EHS}} \cdot \left\{ \left[1 + \frac{1}{4} 10^{0.1(L_E - L_{EHS})} \right]^{0.25} - 1 \right\} \qquad (2)$$

Broadband sounds are treated as a type of summation of several, critical-band wide, sounds [8]. However, at each critical band rate value z, only the largest specific loudness is retained. The others are discarded. This provides the masking characteristic observed in the human ear.

The sloped curves used for determining the decreasing upper tails of specific loudness in reference [4] do not have a mathematical representation, a fact which is very relevant for programming a loudness calculator [8]. Lookup tables must be used to determine the proper value of the slope at a given critical band rate and level. Actually, the slope is frequency-dependent below about 900 Hz [8]; above this frequency it is a function of level only. To this point, it was assumed that the available input data was in the form of critical band levels. Since this is quite uncommon and also in order to more closely mirror ISO 532 B, modifications are included to permit the use of 1/3 octave band levels instead.

The first step is to combine the low-frequency 1/3 octave bands as in the graphical procedure. However, an additional factor is considered: the threshold of hearing is taken into account for the lowest frequencies (up to 63 Hz) and if the 1/3 octave level is below the threshold, no contribution to loudness occurs [8]. After the first three critical bands are approximated in this way, subsequent critical bands are approximated by full 1/3 octave bands as in the graphical procedure. This approximation introduces an error into the loudness calculation which is neglected in the graphical procedure due to its own inherent inaccuracies. For the numerical method, an additional correction is introduced based on the ratio of the approximated and exact critical bands [8].

It was noted by Paulus and Zwicker [8] that the loudness level determined in the graphical procedure will differ from the calculated one if the loudness is less than 0.5 soneG. This is due to additional nonlinearities in the human hearing system that the equation-based method does not inherently account for.

Because of the fact that lookup tables are used to determine the upper slopes of specific loudness, the slopes are constant over each segment and thus an accurate integration may be done using a simple trapezoid rule method [8]. Finally the loudness level can be calculated from

$$L_N = 10\log_2 N + 40 \quad (3)$$

The results obtained from the program agree with those from the ISO graphical procedure within the repeatable accuracy of the graphical method for all sounds with loudness above 0.5 soneG. Below this loudness, additional calculations to account for the nonlinear scale in the graphical procedure below 0.5 soneG would need to be included. This was addressed by Zwicker et al. [15]. Reference [14] contains an identical program written in BASIC instead of FORTRAN. Both programs are able to account for the differences in loudness that result from the sound field being diffuse as opposed to free [7, 15].

2.2.2 Method 2: from reference [15]

While the programs in references [8] and [14] aimed to produce results in close agreement with ISO 532 B, a more recent standard, DIN 45631, exists for calculating loudness. This standard contains a BASIC program for calculating loudness that is different than the program developed by Zwicker et al. [14]. A different program, also by Zwicker et al. [15], which produces the same results as the original DIN standard's program was published in 1991 and claims to calculate loudness values that are "in line" with ISO 532 B. In reference [15], much of the lookup table data is slightly different than in reference [14], the most significant of these differences being that the lookup tables for the upper slopes for accessory loudness contain 18 division levels instead of 16 as they do in reference [8]. Also, the program in reference [15] contains a modified loudness level formula for cases when the loudness is less than 1.0 soneG. This low-loudness formula is

$$L_N = 40(N + 0.0005)^{0.35} \quad (4)$$

with a further correction that if the loudness level so calculated is less than 3 phonGF, then the loudness level in set equal to 3 phonGF. Other than these differences, the programs are similar.

3. SOUNDS TESTED, EXPERIMENTAL SETUPS AND PROCESSING SYSTEMS USED

A comparison of the results for loudness computed from various methods was investigated in this study. To do so, two sounds were used as inputs. Both are described along with the measurement method used below. The data and calculation methods used are also described.

3.1 Sounds Tested and Experimental Setups

Both a 1 kHz tone and pink noise were tested. These are commonly used sounds in psychoacoustic evaluations.

3.1.1 1 kHz Tone

Given that the reference sound for loudness is a 40 dB SPL, 1 kHz tone, this sound was included in the test to see how close the various processing systems came to achieving the theoretical value of 1 sone. In addition, a 1 kHz tone at 80 dB SPL was also tested in order to compare with the pink noise tested. Both tones were generated via a signal generator and acquired at calibrated levels using a data acquisition system.

3.1.2. Pink Noise

Pink noise was played through a Peavey PR10 speaker located on a table 0.73 m off the floor. A microphone was placed directly in line with the speaker at a distance of 2.0 m and at a height of 1.03 m, corresponding to the vertical centre of the speaker. Data was recorded using both a Larson-Davis System 824 sound level meter (SLM) and a multi channel 01dB Orchestra acquisition system. Two 30 second samples were recorded. The overall A-weighted SPL during the tests was 80 dBA.

3.2. Loudness Calculation Processing Systems

A total of eight combinations of 1/3 octave input data and processing methods (See Table1 for details) were used for the pink noise, and six combinations were used for the pure tones in order to be able to properly compare all available methods.

3.2.1. Input Data

Two basic sources of input data were available. The SLM

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

TABLE 1. Combinations considered.

directly provided 1/3 octave band levels of the measured sources, while the 01 dB system using the Orchestra and computer records raw data for later analysis. This file can be processed to give 1/3 octave band levels. This filtering process was accomplished in several ways. The 01dB software, dBFA [16], filters the data according to IEC 61260 [17]. The 01dB software dBSonic uses an unknown internal filtering algorithm. The MATLAB program [18], written by Hastings, filters according to ANSI S1.11-1986 [19]. An update to this standard was published in 2004 [20] which is essentially identical to the IEC standard.

3.2.2. Processing Methods

Five processing methods were used for this study. These were:

- a Microsoft Excel Visual Basic program adapted from reference [14]
- a Microsoft Excel Visual Basic program adapted from reference [15]
- the 01dB software dBFA
- the 01dB software dBSonic
- a MATLAB program [18] based on reference [15]

The two Visual Basic (VB) programs were written by the present authors. dBFA, dBSonic and the MATLAB program process the signal in a two-step process. First, the Orchestra data is converted to 1/3 octave data. Then, this data is fed into the loudness calculator. With dBFA and dBSonic, both of these steps occur within the program with the 1/3 octave data also available for output. With the MATLAB code, the Orchestra to 1/3 octave data conversion can be skipped and the 1/3 octave band levels can be supplied directly.

3.2.3. Combinations used

In order to compare the processing methods and input data, eight combinations were developed. Table 1 lists the combinations in terms of which 1/3 octave band levels and processing system was used for each. These combinations prove sufficient to allow a detailed analysis of the results obtained. For the 1 kHz tone, combinations 1 and 3 were not considered for the reasons outlined above.

4. RESULTS AND DISCUSSION

This section presents the results, analysis and discussion of the tests.

4.1. Results

The loudness results for both types of sounds are shown in Figures 3 and 4. Note that the loudness metric is soneGF, where the G indicates that the loudness was determined from 1/3 octave bands and the F indicates that the sound field was in the free-field condition. Also, when examining the figures, the legend information is to be read from left to right sequentially to correspond to the amplitude bars.

For the 40 dB tones, the Excel (ISO) method using IEC 1/3 octave data from dBFA, dBSonic, and the Hastings (DIN) method using ANSI 1/3 octave data yield the correct result of exactly 1 soneGF. Hastings (DIN) with IEC filtering gives only 0.93 soneGF, which is identical to the Excel (DIN) with IEC filtering result. dBFA over-predicts the loudness to be 1.05 soneGF. 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 soneGF respectively. All other methods significantly under-predict the loudness: Excel or Hastings (DIN) with IEC filtered data give 14.3 soneGF, and Excel (ISO) with IEC filtering gives 14.8 soneGF. Thus for the two sets of tones – the simplest sounds for which one can compute the loudness – only dBSonic and DIN with ANSI filtering give consistently accurate loudness values.

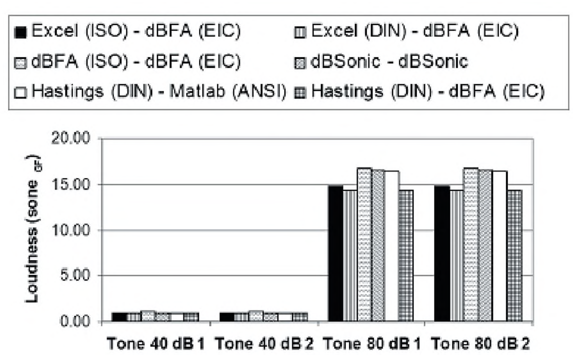

Figure 3. Loudness results for tone measurements.

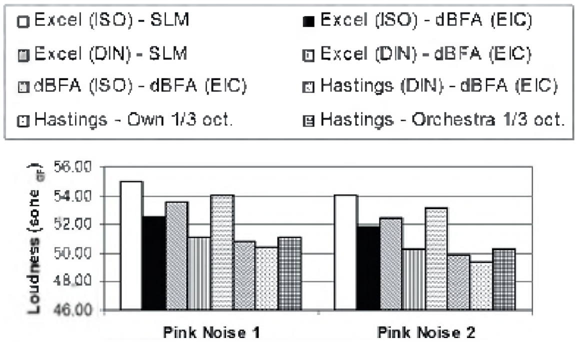

Figure 4. Loudness results for pink noise measurements.

In addition to the methods used for the tones, the pink noise was also analysed using the sound level meter (SLM) which contains its own filtering method. These results were processed through ISO and DIN loudness routines. Based on the results from the tones, dBSonic and DIN with ANSI filtering will be taken as "correct" or reference values of loudness, against which the other methods will be compared. The two agree well for the pink noise measurements, deviating by at most 0.5 soneGF. The numerical values are presented in Table 2. For the pink noise, DIN with IEC filtering yields results that are quite close to the reference values – 51.1 soneGF and 50.3 soneGF for sample 1 and 2, respectively. dBFA over-predicts for both samples by about 3 soneGF. ISO with IEC filtering and both ISO and DIN with the SLM filtering all over-predict the results as well.

In the next section, these results will be analyzed in-depth.

4.2 Analysis and Discussion

Several aspects of the results raise the need for further analysis or detailed discussion. These include the dependence of the results on the 1/3 octave filtering method used, the sources of error in the "incorrect" methods, the differences between loudness and SPL, the differences in loudness between ISO and DIN, and the practical precision limits on loudness.

4.2.1. Filtering Dependency

By looking at the results of the DIN loudness calculations using 1/3 octave data filtered via IEC 61260, ANSI S1.11, or using the SLM, it becomes apparent that there is more than just the loudness calculation routine that affects the final value obtained. From Figure 5 and Table 3 the differences in the results are clear.

Sample:	1	2
dBSonic	50.8	49.9
DIN + ANSI	50.4	49.4

TABLE 2. Pink noise results for dBSonic and DIN with ANSI (soneGF).

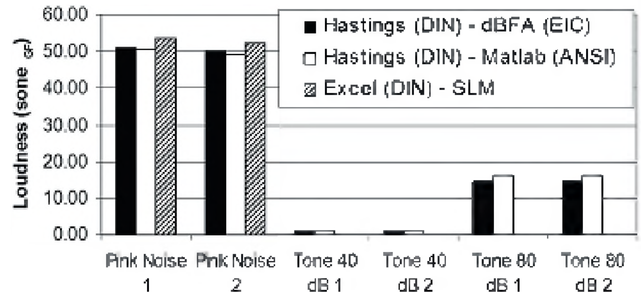

Figure 5. Loudness calculated using DIN with IEC, ANSI and SLM 1/3 octave band filtering.

Sound	IEC	SLM	Maximum
Pink Noise 1	1.37%	6.29%	6.29%
Pink Noise 2	1.84%	6.26%	6.26%
Tone 40 dB 1	-7.30%	N/A	-7.30%
Tone 40 dB 2	-7.30%	N/A	-7.30%
Tone 80 dB 1	-12.86%	N/A	-12.86%
Tone 80 dB 2	-12.86%	N/A	-12.86%

TABLE 3. Error between ANSI, IEC and SLM results (reference: ANSI) for DIN loudness

Between IEC and ANSI, the differences are small but significant (> 1%) for all sounds but the large deviations for the tones should be noted. This is not what would be expected, since if any sound could be expected to be accurately predicted by any loudness calculation, it would be the 1 kHz tone which is the reference sound for loudness. The differences between the SLM and ANSI data are even more significant. The implication is that differences in the frequency spectra of the sounds are responsible for the differences in the errors obtained. The filtering method plays a significant role in defining the accuracy of the loudness calculation. Thus, the same loudness calculation procedure will yield different results when a different method of 1/3 octave band filtering is used. While this result may seem obvious when stated this way, it is often overlooked. There is no mention of the method whereby the 1/3 octave band levels used in the computation should be acquired in ISO 532 B [3], nor in the numerical methods described in references [8], [14] and [15]. Recall that reference [15] contains an identical program to DIN 45631 [4]. This is a significant oversight in the specification of these standards and does little to instill confidence in the results obtained via their use.

4.2.2. Sources of Error

The large deviations of the majority of the loudness calculation methods from the two determined to be "correct"

– dBSonic and DIN with ANSI filtering – require some investigation. For the pink noise, the "incorrect" methods all over-predict the loudness by varying amounts. It is interesting that this over-prediction is not unilateral. The loudness values for the tones are under-predicted by the same methods, except dBFA which always over-predicts the loudness. Sources of error include the differences in filtering methods (as discussed above), as well as differences in lookup table data between the programs given in references [8] and [15].

4.2.3. Loudness vs. Sound Pressure Level

In Section 3 it was stated that all the sounds gave an A-weighted SPL of 80 dBA. The "A" scale was chosen as it is the most commonly used weighting used in acoustics when attempting to deliver a better impression of human perception than a linear SPL [21]. Figure 6 and Table 4 show the loudness values obtained for the different sounds. In the table, the values for mean loudness were calculated by taking the average of the loudness for the samples and across both "correct" methods: dBSonic and DIN with ANSI filtering. The loudness values for these sounds vary greatly: the pink noise has a loudness about three times higher than the 1 kHz tone. Thus, it is evident that overall SPL does not illustrate the entire story. This result should not be surprising given that the bandwidth of the pink noise is large compared to that for the 1 kHz tone. Figure 7 shows the specific loudness vs. critical band rate curves for the tone and pink noise, respectively. The area under the pink noise curve is much larger than the area under the tone's curve, leading to the greater loudness value.

4.2.4. ISO vs. DIN

It is interesting to compare results for ISO and DIN given the same 1/3 octave band inputs. Even though the ISO with SLM and IEC filtering was shown to give incorrect loudness values as compared to the reference methods, this comparison is still useful since ISO is after all an international standard in wide use. Tables 5 and 6 provide these comparisons for SLM and IEC filtering, respectively. The error varies from 2.63% to 7.95%. The statement in reference [15] that DIN 45631 gives results "largely identical" to ISO 532B is somewhat of an exaggeration. Also, it can be noted that ISO always produces a higher loudness than DIN for the same input data.

4.2.5. Precision and Accuracy Limits of Loudness

As a final observation, given the empirical nature of the data used in the calculation of loudness and the dependence of the final values obtained on calculation and filtering method(s), it may not be meaningful to report loudness values with too great of a precision. Single decimal place precision is the best that one should be expected to report and expect to be significant.

In practice, the best accuracy that should be expected is about ±0.5 sone, though often the margin of error will be even larger. Recall that loudness is a measure of the human perception of the intensity of a sound and that commonly, it is said that a 3 dB change in SPL is the minimum perceptible by the human hearing system. Also, for mid-frequency tones above 40 phons, a 10 dB-increase in the SPL corresponds approximately to a doubling of its loudness [2]. Consider the 80 dB, 1 kHz tones presented. With an SPL of 80 dB, the loudness is about 16.5 soneGF. According to the power law described in [2], a just-perceptible change to 83 dB would result in a new loudness of 19.7 soneGF. This is a change of 3.7 sone! So, here the practical accuracy limit would be a range of this magnitude, that is, ±1.8 sone. There is clearly a significant error margin in all loudness computations.

While the same doubling formula cannot really be applied to sounds other than tones, it can be assumed to give a rough estimate and so the ±1.8 sone accuracy can still be assumed as a first approximation. Even given this relatively generous margin of error, the deviations amongst the results are

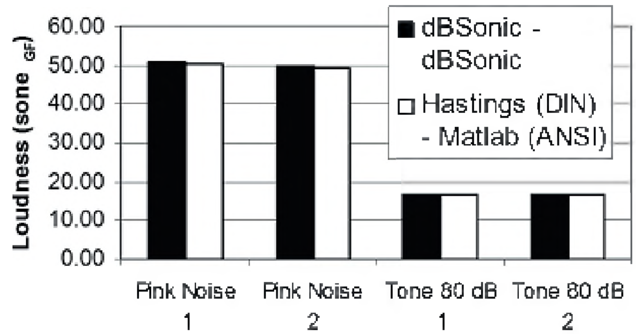

Figure 6. Loudness comparisons.

Sound	Pink Noise	80 dB, 1 kHz tone
Loudness ($sone_{GF}$)	50.1	16.5

TABLE 4. Comparison of mean loudness for the sounds tested

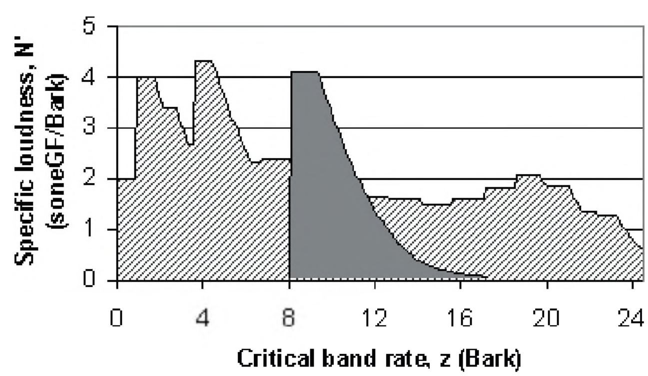

Figure 7. Specific loudness vs. critical band rate for the 80 dB, 1 kHz tone (filled) and pink noise (crosshatched).

	ISO (sone$_{GF}$)	DIN (sone$_{GF}$)	% error (reference: DIN)
Pink Noise 1	54.9	53.5	2.63%
Pink Noise 2	54.0	52.5	2.99%

TABLE 5. ISO and DIN loudness for SLM data.

	ISO (sone$_{GF}$)	DIN (sone$_{GF}$)	% error (reference: DIN)
Pink Noise 1	52.6	51.1	2.96%
Pink Noise 2	51.8	50.3	3.09%
Tone 40 dB 1	1.0	0.9	7.95%
Tone 40 dB 2	1.0	0.9	7.95%
Tone 80 dB 1	14.8	14.3	3.84%
Tone 80 dB 2	14.8	14.3	3.84%

TABLE 6. ISO and DIN loudness for IEC data.

Sound	Maximum deviation (sone)
Pink Noise 1	4.6
Pink Noise 2	4.7
Tone 80 dB 1	2.4
Tone 80 dB 2	2.4

TABLE 7. Maximum deviations from correct values for 80 dBA sounds,

still significant as can be seen in Table 7. The maximum deviation was calculated by taking the difference between the highest and lowest loudness values for a sound. Although these deviations are outside of what should be considered as a reasonable margin of error, they do not seem quite so large when viewed in this light.

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 at 80 dBA were used to compare several 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 the dBSonic (using internal filtering) and DIN with (old) ANSI filtering methods. The program based on ISO does not yield an accurate measurement in most cases.

The calculation of loudness from 1/3 octave band levels cannot be separated from the 1/3 octave band filtering process, as different methods of filtering (SLM, IEC, ANSI) all result in different loudness values even when processed using a single calculation method. This dependence is ignored in the literature reviewed.

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 soneGF, as would be expected due to differences in frequency content. Finally, one should be cautioned not to state values with too great an accuracy when dealing with loudness. Generally the error will be in the range of ±0.5 to 2.0 sone.

Topics for further study include an in-depth analysis of the 1/3 octave spectra as well as the specific loudness curves of the sounds for the different filtering methods. The goal would be to pinpoint the contributions that lead to different loudness values, as well as the consideration of other combinations such as ISO loudness with ANSI filtering.

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