Ottawa, Canada
INTER-NOISE 2009
2009 August 23-26

Standards for calculating loudness of stationary or time-varying sounds

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ABSTRACT

For pure tones at 1 kHz with different levels loudness values from ANSI S3.4-2007 or DIN 45631 (1991) are essentially the same. Deviations of calculated values from loudness values expected on the basis of subjective evaluations amount to a maximum of 5 % in line with the accuracy possible in loudness experiments.
However, for pink noise of different levels, ANSI S3.4-2007 gives systematically higher loudness values than DIN 45631 (1991). The magnitude of the relative differences depends on level and reaches factors between 1.27 and 2.31 for the levels considered.
Interestingly, when shifting the curve obtained for pink noise from ANSI S3.4-2007 by 5 dB towards higher levels, it almost coincides with the curve obtained from DIN 45631 (1991).
Technical sounds usually produce time-varying loudness functions which can be assessed using DIN 45631/A1 (2008). More or less extreme examples are given for a planing machine and a jackhammer.

1. INTRODUCTION

For calculation of the loudness of stationary sounds, ISO 532 (1975) proposes two methods which both are based on results of psychoacoustic experiments, but differ in detail. Method A is based on studies of S. S. Stevens, method B on studies of E. Zwicker. Since the work on these methods started already in the 1960ties it is expected that ISO will replace the old material by more recent algorithms like ANSI S3.4-2007 or DIN 45631 (1991).
However, for practical applications in technical acoustics, standards are necessary, which can handle not only stationary but also strongly time-varying sounds. To fulfill these requirements, the new standard DIN 45631/A1 has been prepared and published in 2008.
In this paper, values of loudness calculated by different algorithms are compared for synthetic as well as technical sounds. The magnitude of possible differences is discussed in view of the precision possible in psychoacoustic experiments on loudness perception.

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2. STANDARDS FOR STATIONARY SOUNDS

A. Loudness of 1 kHz tones

The standards described in ISO 532 for loudness calculation of stationary sounds are based on graphical procedures. In the meantime, computer programs got available which in principle are based on the procedures, but got refinement. For the procedure described in ISO 532B a computer program was published in DIN 45631 (1991). In addition to replace the sometimes tedious graphical work, the computer program also includes some specifications *how* to implement the influence of equal loudness contours at low frequencies. The DIN 45631 (1991) standard includes the listing of a computer program in Quick Basic. To ease the application an applet was published (http://www.mmk.ei.tum.de/~kes/LoudnessMeter/index.html) where only the third-octave band spectra have to be entered and loudness is automatically calculated in sone. In addition it has to be specified, whether the third-octave band spectra were obtained in free or diffuse sound field.
As kind of an update of ISO 532A the standard ANSI S3.4-2007 was published. Annex B of this standard introduces a computer program which can be obtained from Brian R. Glasberg and Brian C. J. Moore of the Department of Experimental Psychology at the University of Cambridge, UK.

Since it may be possible that ANSI S3.4-2007 and DIN 45631 (1991) will replace parts A and B in a revised ISO 532 standard for the loudness of stationary sounds, it is of interest to compare results obtained by these standards for synthetic sounds. Since many technical sounds are time-varying, examples will be described in section 3.

The comparison for pure tones at 1 kHz seems to be of particular importance since historically subjective loudness evaluation has been assessed by comparing the loudness of a sound with a 1 kHz tone of same loudness, leading to the phon scale.
ANSI S3.4-2007 gives in Annex A Example 1 loudness values for pure tones at 1 kHz with levels between 10 and 80 dB. For comparison, the loudness values calculated according to DIN 45631 (1991) were determined. When entering the third-octave spectra into the applet mentioned above, the finite attenuation of the filter slopes has to be considered. For example, a 1 kHz tone with an SPL of 60 dB elicits in the 1 kHz filter 60 dB as expected, but also 40 dB in the surrounding filters at 800 and 1250 Hz, 20 dB in filters at 630 and 1600 Hz and so forth.
The results displayed in Table 1 enable a comparison of the loudness values obtained by ANSI S3.4-2007 versus DIN 45631 (1991).

Table 1: Comparison of loudness values obtained for 1 kHz tones at levels between 10 and 80 dB using ANSI S3.4-2007 versus DIN 45631(1991).

$L_{1\,kHz}$	10	20	30	40	50	60	70	80	dB
N_{ANSI}	0.03	0.14	0.42	1.0	2.1	4.2	8.1	16.0	sone
N_{DIN}	0.02	0.13	0.42	1.00	2.01	4.01	8.02	16.07	sone
ΔN_{ANSI}				0	5	5	1.25	0	%
ΔN_{DIN}				0	0.5	0.25	0.25	0.44	%

The data displayed in Table1 show rather similar loudness values for 1 kHz tones calculated by ANSI S3.4-2007 versus DIN 45631 (1991). For levels above 40 dB, loudness should double from 1 sone for each increase by 10 dB. The deviations of the calculated loudness values from the expected loudness values are rather small and never exceed 5 %. The corresponding level differences amount according to the formula

$$L = \left[\left(33.22 \cdot \lg \frac{N}{sone} \right) + 40 \right] dB$$

to a maximum of about 0.7 *dB*. This level difference is in the same order of magnitude as the reproducibility of subjective loudness ratings.

In summary it can be stated that for 1 kHz tones both ANSI S3.4-2007 and DIN 45631 (1991) yield results which are in line with subjective evaluations; the differences between the calculated loudness values are in the same order of magnitude as the reproducibility of subjective loudness ratings.

B. Loudness of pink noise

Loudness of pink noise is described in ANSI S3.4-2007 Annex A Example 4. Levels within third-octave bands are given. Since the human hearing system encompasses about 30 third-octave bands, the overall level of the pink noises can be estimated according to the formula

$$L_{pn} = L_{to} + 10 \cdot \lg 30 dB$$

For example pink noise with a third-octave level of L_{to} = 30 *dB* shows an overall level of about L_{pn} = 45 *dB*.
In figure 1, calculated loudness values of pink noise are plotted as a function of overall level. Rhombs connected by dashed lines represent loudness data given in ANSI S3.4-2007; stars connected by dotted lines indicate loudness data calculated according to DIN 45631 (1991).

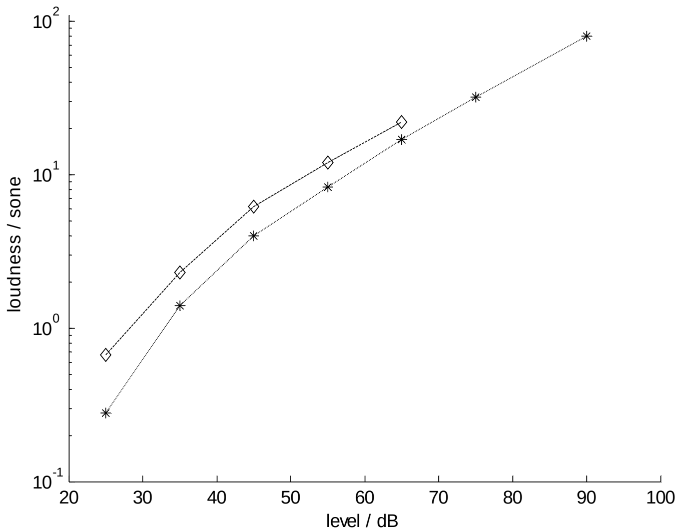

Figure 1: Loudness of pink noise as a function of its overall level. Rhombs connected by dashed lines represent loudness data given in ANSI S3.4-2007; stars connected by dotted lines indicate loudness data calculated according to DIN 45631 (1991).

The data plotted in figure 1 clearly reveal that for pink noise, loudness values given in ANSI S3.4-2007 Annex A Example 4 (rhombs) always are higher than the loudness values calculated according to DIN 45631 (1991) (stars).
This discrepancy can not be overcome by just multiplying the loudness values calculated according to DIN 45631 (1991) by a constant factor to reach the values given in ANSI S3.4-2007 Annex A Example 4. At 50 dB third-octave band level for example, the factor necessary would be about 1.37; however, at 30 dB third-octave band level the factor would be about 1.58.
When, however, the dashed curve derived from ANSI S3.4-2007 is shifted by 5 dB towards higher levels it almost coincides with the dotted curve calculated according to DIN 45631(1991). This reasoning is illustrated in figure 2.

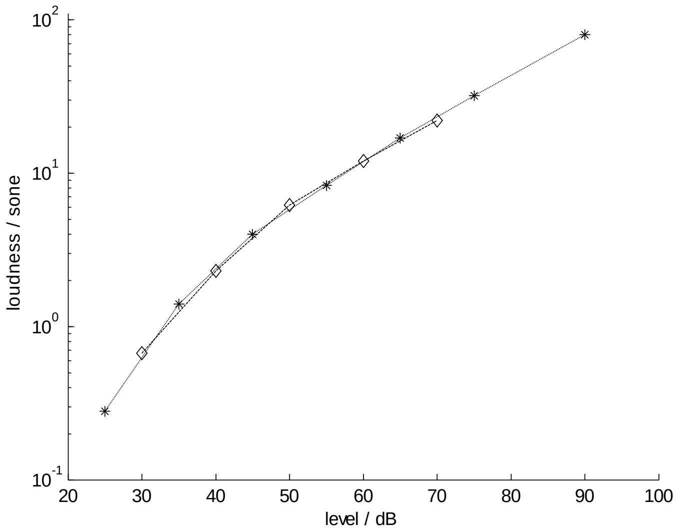

Figure 2: Same as figure 1, but dashed curve shifted by 5 dB towards higher levels.

For broadband sounds like pink noise, loudness values calculated according to ANSI S3.4-2007 versus DIN 45631 (1991) differ significantly: Loudness values for ANSI S3.4-2007 are by a factor between 1.37 and 2.31 higher than values for DIN 45631 (1991). These differences are much larger than variations in subjective estimates of loudness perception.
However, for pink noise these differences in loudness values can be minimized when the curve derived from ANSI S3.4-2007 is shifted towards higher levels or the curve obtained from DIN 45631(1991) is shifted towards lower levels.

3. STANDARD FOR TIME-VARYING SOUNDS

Since many technical sounds as well as speech and music are time-varying sounds, for practical applications a standard is necessary which also accounts for the loudness of time-varying sounds. To this end, the German standard DIN 45631/A1 was developed and published in 2008. In addition to spectral effects also temporal effects like post masking or temporal integration are assessed in line with features of the human hearing system. There are several software packages on the market which maintain to implement DIN 45631/A1 (2008). To enable the user to check the quality of an actual implementation, test signals are provided together with the standard. The output of the loudness algorithm in question can be compared to reference curves with target

values and margins of error. In addition, reference loudness values for the test signals are given in the standard as tables. Prescribed time functions of specific loudness as well as overall loudness have to be fulfilled.
For the loudness calculations shown in the following, an implementation of DIN 45631/A1 (2008) was used which fulfills all requirements, i.e. the loudness values given for the test signals either are on target or at least within the allowed margin.
As more or less extreme examples for technical sounds two sounds from the acoustic demonstrations available at http://www.mmk.ei.tum.de/~tal/demos/lautheit.html were chosen: Sound #5 from a planing machine represents an almost stationary sound whereas sound #6 from a jackhammer can be considered as a typical time-varying sound. To enable a comparison of loudness calculations according to standards for stationary versus time-varying sounds, two types of analysis were performed: On the one hand, third-octave band spectra were determined and loudness according to DIN 45631 (1991) was calculated using the applet given in http://www.mmk.ei.tum.de/~kes/LoudnessMeter/index.html. On the other hand, using a loudness analyzer which fulfills the requirements described in DIN 45631/A1 (2008) loudness-time functions were calculated.
Figure 3 shows the loudness-time function for the sound of a planing machine determined according to DIN 45631/A1 (2008) as solid curve. For comparison the loudness calculated according to DIN 45631 (1991) is given as dotted line.

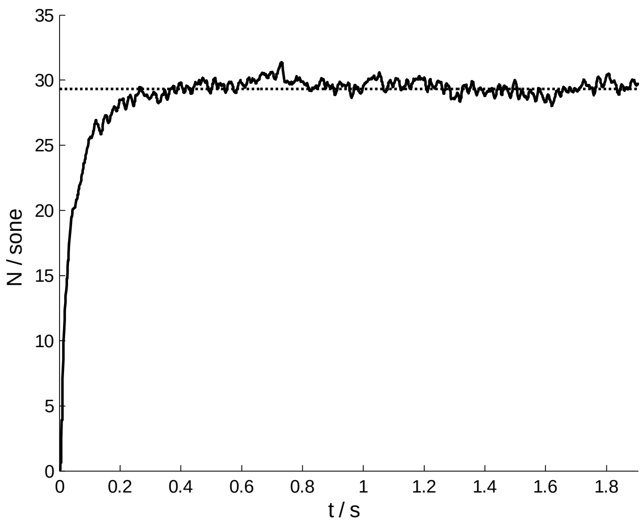

Figure 3: Loudness-time function for the sound of a planing machine (solid) calculated according to DIN 45631/A1 (2008) in comparison to the loudness value (dotted) calculated according to DIN 45631 (1991).

The data displayed in figure 3 indicate that the loudness-time function (solid) shows only little variation. After a settling time of say 0.4 seconds, the deviations from the loudness value calculated for stationary sounds (dotted) amount on the average to some 5 % and therefore are in the same order of magnitude as the accuracy of the subjective loudness evaluations. As expected, loudness of more or less stationary technical sounds can be described by both DIN 45631 (1991) as well as DIN 45631/A1 (2008).

Figure 4 shows the loudness-time function for the sound of a jackhammer determined according to DIN 45631/A1 (2008) as solid curve. For comparison the loudness calculated according to DIN 45631 (1991) is given as dotted line.

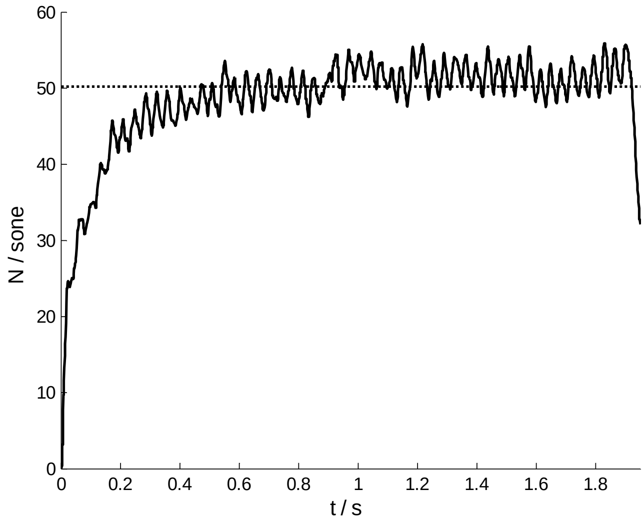

Figure 4: Loudness-time function for the sound of a jackhammer (solid) calculated according to DIN 45631/A1 (2008) in comparison to the loudness value (dotted) calculated according to DIN 45631 (1991).

The data displayed in figure 4 indicate that the loudness-time function (solid) shows strong temporal variations. After a settling time of say 0.4 seconds, the deviations from the loudness value calculated for stationary sounds (dotted) amount on the average to more than 10 %. A clear temporal structure is visible which adds to the annoyance of the sound. This additional feature can either be assessed by a spectral analysis of the loudness-time function or an analysis simulating the hearing sensation roughness.

In summary, it is highly recommended to use for the measurement of the loudness of technical sounds DIN 45631/A1 (2008) since it can assess not only stationary sounds but also strongly time-varying sounds.

4. CONCLUSIONS

The loudness of synthetic sounds like pure tones or pink noise can be assessed by standards for stationary sounds like ANSI S3.4-2007 or DIN 45631 (1991). For technical sounds, loudness calculations according to the standard DIN 45631/A1 (2008) are recommended since the loudness-time functions reflect temporal variations important for annoyance studies as well as questions of sound engineering and sound quality design.

REFERENCES

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[3] DIN 45631/A1 (2008), “ Berechnung des Lautstärkepegels und der Lautheit aus dem Geräuschspektrum – Verfahren nach E. Zwicker – Änderung 1: Berechnung der Lautheit zeitvarianter Geräusche”
[4] ISO 532 (1975), “Method for calculating loudness level”