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MODELING THE ISO 226:2023 EQUAL-LOUDNESS-LEVEL CONTOURS BY STANDARDIZED LOUDNESS METHODS

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ABSTRACT

The standard ISO 226 [1] specifies combinations of sound pressure levels and frequencies of pure continuous tones that are perceived as equally loud by human listeners. These equal-loudness-level contours are part of the foundation of the psychoacoustic research and are constantly evolving. The recent third version of ISO 226:2023 contains some minor corrections to the second version of ISO 226:2003. In this paper, we describe these changes and evaluate how well current standardized algorithms perform in generating the new ISO 226:2023 curves. To this end, we compare the loudness methods published in ISO 532-1:2017 (Zwicker method) [2], ISO 532-3:2023 (Moore, Glasberg and Schlittenlacher method) [3], and the Sottek Hearing Model Loudness method published in ECMA 418-2 2nd edition (2022) [4]. It should be noted that the Zwicker method aims to match the equal-loudness-level contours of the first edition of ISO 226:1987, whereas the other methods aim to match the data of the second version of ISO 226:2003.

Keywords: *Equal-Loudness-Level Contours, Sottek Hearing Model, ISO 226:2023, Loudness, ECMA 418-2.*

1. INTRODUCTION

Equal-loudness-level contours provide the foundation for many loudness methods, which underpin various psychoacoustic analyses such as roughness [4] and sharpness [5]. Consequently, it is essential that modern loudness methods can adapt to improvements in equal loudness contours, as described in ISO 226. In this brief paper, we examine the performance of modern standardized loudness methods – ISO 532-1, ISO 532-3 and ECMA 418-2 – with respect to the latest version of the ISO 226 standard.

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2. CHANGES IN ISO 226:2023

The updates in ISO 226:2023 include clarification of the scope of the standard, an updated bibliography, an alignment with the 2019 revised edition of ISO 389-7 [6] regarding the 0-phon data, and corrections of systematic errors in the equal-loudness-level contours. The updated introduction emphasizes that the equal-loudness-level contours are only applicable to pure tones, since there are insufficient data to estimate their validity for other sound types such as broadband noise and noise with prominent tones. Thus, while ISO 226 serves as a validation and requirement for loudness methods, appropriate and validated loudness models should be employed for other sound types. The systematic errors previously present in the standard resulted in a maximum change of less than 0.6 dB, which is relatively small. These corrections resulted in an updated formula for determining the sound pressure level from the loudness level and an updated reference table with new parameters. The new formula that relates sound pressure level L_f in dB and loudness level L_N in phon is as follows:

$$L_f = \frac{10}{\alpha_f} \cdot \lg\{(4 \cdot 10^{-10})^{(0.3-\alpha_f)} \cdot [10^{0.03\frac{L_\mathrm{N}}{\mathrm{phon}}} - 10^{0.072}] + 10^{\alpha_f \frac{T_f + L_\mathrm{U}}{10\,\mathrm{dB}}}\}\,\mathrm{dB} - L_\mathrm{U} \quad (1)$$

in which T_f is the threshold of hearing, α_f is the exponent for loudness perception, L_{U} is the magnitude of a linear transfer function normalized at 1 kHz in dB. The new values of α_f, L_{U} and T_f are available in tabular format in ISO 226:2023 [1].

3. SOTTEK HEARING MODEL

The ECMA 418-2 standard is based on the Sottek Hearing Model [7], which accounts for numerous aspects of auditory perception, including outer/middle ear filtering, auditory filter bank, and the compressive non-linearity of the human auditory system. The Sottek Hearing Model, which serves as the foundation for the ECMA 418-2 standard, was recently employed in the development of a new standardized loudness metric that considers both the tonal and noise loudness of signals. This new loudness standard effectively handles the loudness of noise signals with sub-critical bandwidth [8] and harmonic components [9].

4. METHODOLOGY

To evaluate the performance of the algorithms, equal-loudness-level contours of 20 phon, 40 phon, 60 phon and 80 phon were calculated, for the frequency range from 100 Hz to 10 kHz. All values for this selection are defined as valid in the ISO 226:2023 standard. For each of the three methods ISO 532-3, ISO 532-1, and ECMA 418-2 we calculated the corresponding sone value at 1 kHz for a given phon level and then determined the necessary dB level for each frequency so that the algorithm yielded the same sone value. This approach enabled us to generate the equal-loudness-level contours of the algorithms. For all methods, we calculated the Root-Mean-Squared (RMS) difference between their results and the reference values of the ISO 226:2023 equal-loudness-level contours.

5. RESULTS

The results of each method can be seen in Fig. (1) to (4), while the RMS difference for each result is shown in Table 1.

Our comparison revealed that the Zwicker method, originally designed to match the contours of ISO 226:1987 (as can be clearly seen in Fig. 2), exhibits a greater deviation from the new ISO 226:2023 standard compared to the other two methods. We also verify a fluctuation in the results. This is a known effect described in Annex D of the DIN 45631/A1 standard [10] (the basis for ISO 532-1 [2]), from which we take the verbatim

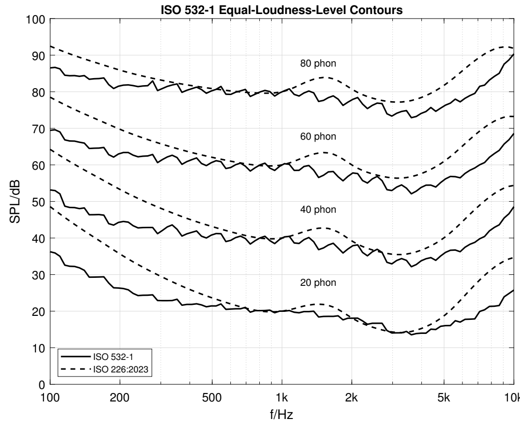

Figure 1: Equal-loudness-level contours of the ISO 532-1 standard compared to ISO 226:2023.

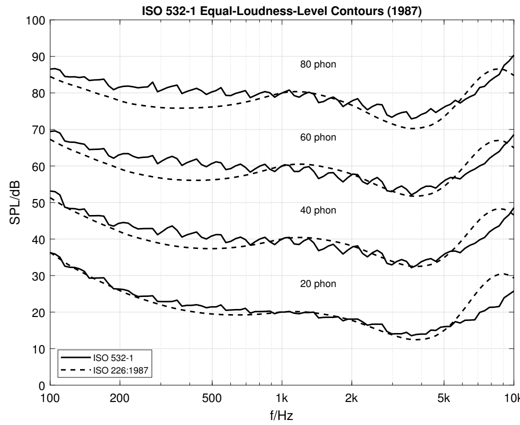

Figure 2: Equal-loudness-level contours of the ISO 532-1 standard compared to ISO 226:1987. Here the RMS difference is 2.84 dB.

Table 1: Difference of each method with respect to the reference equal-loudness-level contours in ISO 226:2023.

Method	RMS difference [dB]
ISO 532-1	5.55
ISO 532-3	3.04
ECMA 418-2	1.57

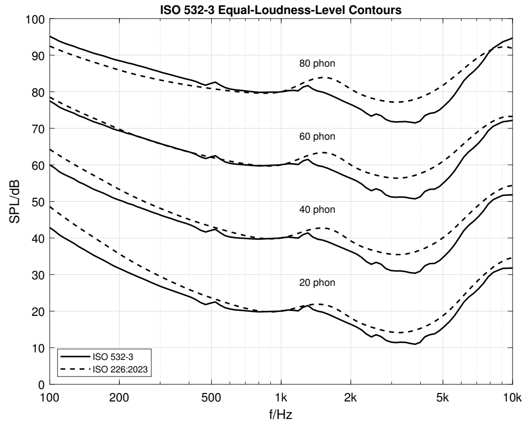

Figure 3: Equal-loudness-level contours of the ISO 532-3 standard compared to ISO 226:2023.

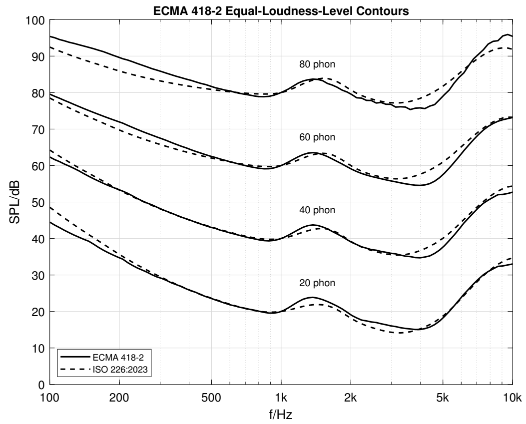

Figure 4: Equal-loudness-level contours of the ECMA 418-2 standard compared to ISO 226:2023.

text: *"For a sliding sine without superimposed noise, one would initially expect a "smooth" progression of loudness according to hearing. However, the actual calculated course is characterized by certain fluctuations. The reason for this is to be found in the signal processing of the third-octave filter bank."* Depending on the characteristics of the implemented filters, deviations of varying magnitude from the "ideal value" can occur in the transition frequency ranges in the addition of the partial loudnesses. The method thus must be used with care, especially for sounds at the edges of the third-octave filters.

In contrast, the Moore, Glasberg, and Schlittenlacher method (ISO 532-3:2023) and the Sottek Hearing Model Loudness method (ECMA 418-2 2nd edition) demonstrate a closer agreement with the updated contours. For middle frequencies between 1 kHz and 5 kHz, the ECMA 418-2 standard has a considerably better match than all other approaches, which overestimate the loudness of tonal components in this range.

It is important to note that these results pertain to raw sine waves under free-field conditions. For noise signals, particularly those with a sub-critical bandwidth, we recommend using the ECMA 418-2 standard, as it better models this type of data, as demonstrated in [8]. The Sottek loudness also has a slightly better accuracy for multi-tone components [9], and since it is additionally the approach with the lowest error here, we see it as a dominant approach with respect to the results, being better or equal in all possible type of signals we investigated so far.

Another interesting point of comparison between the methods is their calulation time. We used the software ArtemiS SUITE from HEAD acoustics to benchmark all methods and to show their normalized calculation time result in Table 2. There we see that the ISO 532-1 is the fastest method, followed by ECMA 418-2 and finally ISO 532-3, which is one order of magnitude slower than the other methods. For the ECMA 418-2 standard, most of the calculation time is due to the separation of tonal and noise components to calculate the corresponding partial tonal and noise loudness values. The algorithm of ISO 532-3, on the other hand, is very time consuming, and even though the code in ArtemiS SUITE is highly optimized, the calculation still takes a long time.

Table 2: Normalized calculation time for each method as calculated with the software ArtemiS SUITE from HEAD acoustics.

Method	Normalized calculation time
ISO 532-1	1
ISO 532-3	22
ECMA 418-2	6

6. CONCLUSION

In this paper, we discussed the changes made in ISO 226:2023 compared to its 2003 predecessor and explained the main reasons for these changes. Using the new equal-loudness-level contours, we evaluated the efficiency of various current loudness standards in replicating these curves.

Our results show that ECMA 418-2 2nd Edition outperformes the others with an RMS error of 1.57 dB, followed by ISO 532-3 with an error of 3.04 dB and ISO 532-1 with an error of 5.55 dB. The first two methods reproduce the curves with reasonable accuracy, while ISO 532-1 shows larger deviations.

The poorer performance of ISO 532-1 was to be expected since it was designed for matching ISO 226:1987, which incorporated substantially different curves. Moreover, ISO 532-1 exhibits fluctuations in its results due to the steepness of the third-octave filters used, which can be particularly challenging for sounds located at the edges of the filters or those with broad frequency modulations.

In the mid-frequency range of 1 kHz to 5 kHz, the Sottek loudness displays significantly superior accuracy than other methods, which tend to overestimate the loudness of signals at these frequencies. In terms of computational efficiency, ISO 532-1 proves to be the fastest method, followed by ECMA 418-2, which is six times slower, and ISO 532-3, which is 22 times slower even with a highly optimized code, making its application to extended signals cumbersome.

Currently, the Sottek loudness defined in ECMA 418-2 has shown equivalent or superior performance in all experiments we have conducted [4, 8, 9] and has established itself as the dominant variant in terms of result quality.

7. REFERENCES

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