Proceedings of 20th International Congress on Acoustics, ICA 2010

23-27 August 2010, Sydney, Australia

Specification and calibration of acoustic short-term stimuli for objective audiometry

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PACS: 43.58.+z, 43.64.+r, 43.66.+y, 43.80.+p

ABSTRACT

Many applications in objective audiometry measure and evaluate responses of the hearing system to acoustic short-term stimuli. One of the earliest and best known among these signals of short duration is the 'reference pulse' specified in standard IEC 60645-3. This definition of an electrical reference signal dates back to times when audiometric equipment essentially consisted of analogue components used in laboratory set-ups. Therefore, overshoot caused by the limited bandwidth of the electrical signal was not considered in this definition. Modern equipment, however, often uses audio-frequency DA converters, which imply a limited bandwidth of the signal path. Even if their sample rate is chosen in such a way that the physiological and psychoacoustic effects of the pulse do not differ from those of the quasi-non-band-limited pulse, the transients caused by DA conversion and bandwidth limitation lead to a time response of the pulse conflicting with the current IEC specification. In order to resolve this problem, a modified definition of the reference pulse by detailed time-domain tolerance diagrams is discussed. Meanwhile, in addition to the 'signals of short duration' specified in IEC 60645-3, a variety of short-term stimuli with considerably different temporal characteristics is available for audiometry. ISO 389-9 explicitly allows the application of these signals, provided that they are clearly specified by the manufacturer. The concept of expressing their reference thresholds by means of peak-to-peak equivalent Reference Equivalent Threshold Sound Pressure Levels (peRETSPLs) is easy to implement, even with rather simple instrumentation. However, this concept results, for some stimuli, in calibration values which do not at all correlate with either the behavioural hearing thresholds or the spectral energy of the signals. Attempts at improving the calibration procedure with respect to these 'inconsistencies' are sketched out in this paper.

INTRODUCTION

Short-term stimuli for objective audiometry, covering the range from basic rectangular reference pulses to sophisticated signals, e.g. chirps optimized to evoke high potentials for hearing screening applications, need to be exactly specified and properly calibrated in order to ensure consistent and comparable measurement results. The basic signals of short duration are specified in standard IEC 60645-3:2007 “Electroacoustics – Audiometric equipment – Part 3: Test signals of short duration” [1]. The definition of the electrical reference pulse for generating click signals is not fully applicable to modern equipment using audio-frequency DA converters, because these imply a limited bandwidth of the signal path, resulting in overshoot and transients. This problem is discussed in the first part of this paper.

Reference hearing thresholds for short-term stimuli are usually expressed by peak-to-peak equivalent Reference Equivalent Threshold Sound Pressure Levels (peRETSPLs) according to ISO 389-6. Though this concept is easy to implement, even with rather simple instrumentation, one of the procedure's drawbacks is the lack of coherence with the behavioural hearing threshold. Even signals with very similar power spectra yield widely spaced reference threshold sound pressure levels. The second part of this paper focuses on practical examples and attempts at improving the calibration of short-term stimuli.

SPECIFICATION OF ELECTRIC REFERENCE PULSE

Standardized reference pulse

The specification of the electric reference pulse in IEC 60645-3 dates back to times when audiometric equipment essentially consisted of analogue components. Overshoot caused by the limited bandwidth of the electrical signal was not considered in the specification: "The reference pulse … shall be an electric rectangular pulse (single monophasic rectangular wave) of (100 ± 10) µs duration with rise and fall times less than 25 µs" [1]. The duration is defined as the time interval between the instantaneous values of 50 % of the signal amplitude; rise and fall time correspond to the time interval between 10 % and 90 % of the signal amplitude, respectively. These requirements are easy to meet if the pulse is generated by means of an electrical function generator with a bandwidth which is much wider than the audio-frequency bandwidth. The oscillogram of a reference pulse generated in this way is shown in Figure 1. The upper waveform (green) is the function generator output signal and the lower one (purple) is the signal measured across the electrical terminals of an audiometric headphone driven by a conventional audiometer.

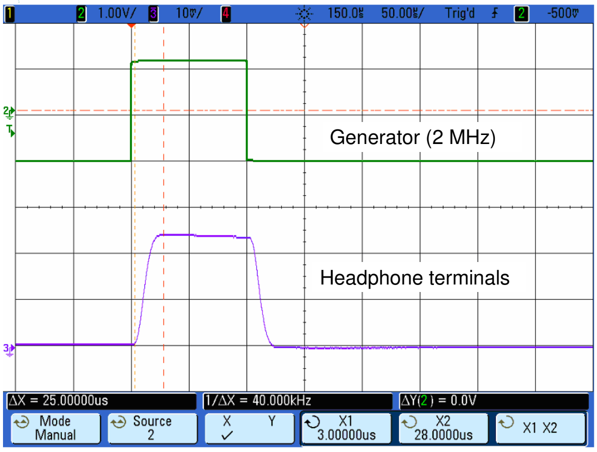


Figure 1. Oscillogram of an electrical reference pulse. Upper waveform: function generator output signal; lower waveform: electrical terminals of audiometric headphone.

Figure 1 proves that the requirements described above are readily observed by the signal at the headphone terminals. There is neither noticeable overshoot nor any other transient oscillation.

Impact of limited bandwidth

Modern audiometric equipment, however, often uses audio-frequency DA converters, which imply a limited bandwidth of the signal path. Usual audio sampling rates give rise to remarkable overshoot and transient oscillations of the electrical output signal. This means that the waveform of the pulse driving the audiometric transducer does not comply with the current IEC 60645-3 specification, which does not allow for any overshoot.

Based on a rough estimation of the achievable rise and fall times as 80 % of the sampling interval, the requirements of IEC 60645-3:2007 could just be met using a sampling frequency of 32 kHz. Audiometric equipment which partly uses sampling rates as low as 16 kHz is definitely unable to generate standardized reference pulses. For such devices, reference hearing thresholds determined using reference pulses according to IEC 60645-3:2007 are not applicable.

Provided that the pulse is appropriately designed in the frequency domain, aiming at optimizing slew rate and overshoot in the time domain, conventional audio DA converters (sampling rate 44,1 kHz), however, are definitely able to generate pulses compliant with the duration and rise/fall-time specifications of IEC 60645-3.

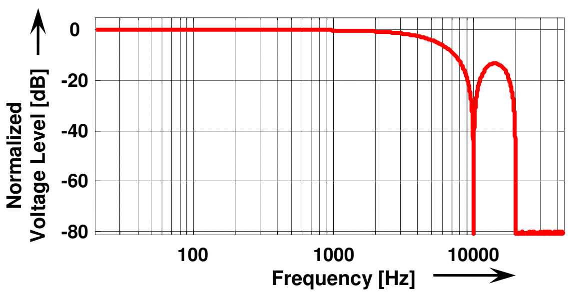


Figure 2. Spectrum $\sin(x)/x$ ($x = \pi \cdot f / f_0$; $f_0 = 10$ kHz) for a 100 µs reference pulse with an upper limiting frequency of 20 kHz.

For a series of listening tests using such a conventional audio DA converter, the rectangular pulse was designed in the frequency domain by the spectral representation of an ideally rectangular pulse with a duration of 100 µs: the sinc function $\sin(x)/x$ (with $x = \pi \cdot f / f_0$; $f_0 = 10$ kHz). The second zero of this function is located at 20 kHz, and all higher frequencies were completely blanked out, see Figure 2. Hence, the pulse has an upper limiting frequency of 20 kHz.

The waveform of this pulse signal, measured across the electrical terminals of an audiometric headphone, easily meets the requirements for duration, rise and fall time, as shown in Figure 3.

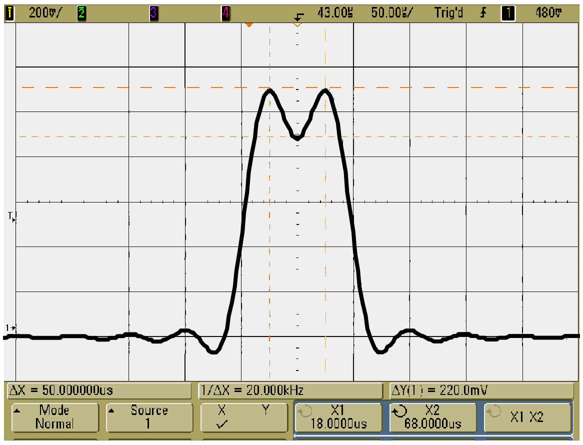


Figure 3. Waveform of the generated reference pulse (44,1 kHz sampling rate); measured by means of an oscilloscope at the headphone terminals; duration: 98 µs; rise and fall time: 22,8 µs; overshoot: 21 %, transient oscillations: 10 % of amplitude.

Overshoot and transient oscillations with the observed magnitude do not essentially influence the technical and psychoacoustic effect of the (acoustical) click, for example, the corresponding reference hearing threshold. This was demonstrated by the listening tests [2].

Time-domain tolerance diagram

A detailed time-domain tolerance diagram was derived from the band limited reference pulse described above. It adds tolerances for ripple and transient oscillations to the basic duration and slew-rate requirements of IEC 60645-3, see Figure 4.

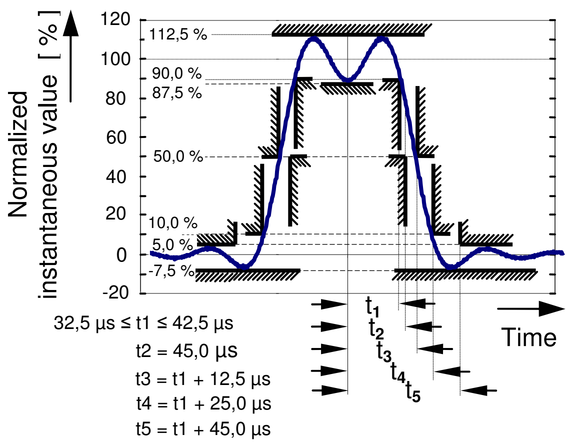


Figure 4. Time-domain tolerance diagram for the electrical reference pulse.

This tolerance diagram allows for an acceptable extent of overshoot and transient oscillations, but, at the same time, sets limits which do not unduly affect reference hearing thresholds and other reference values, determined with pulses according to the current specification in IEC 60645-3:2007.

Standardized electrical reference pulses according to this tolerance diagram would be applicable both for the laboratory determination of audiological characteristics and for on-site practical audiometry.

CALIBRATION OF SHORT-TERM STIMULI

In addition to the 'signals of short duration' specified in IEC 60645-3, a variety of short-term stimuli with considerably different temporal characteristics is available for audiometry. ISO 389-9 explicitly allows the application of these signals, provided that they are clearly specified by the manufacturer.

Peak-to-peak equivalent Reference Equivalent Threshold Sound Pressure Level (peRETSPL)

The concept of expressing reference thresholds of short-term stimuli by means of peak-to-peak equivalent Reference Equivalent Threshold Sound Pressure Levels (peRETSPLs) according to ISO 389-6 is easy to implement, even with low-level instrumentation. Both for the determination of the reference hearing thresholds with a group of otologically normal subjects and for the calibration of audiometers, all that is needed is (1) a signal generator, (2) an ear simulator or an acoustical coupler with a calibrated measurement microphone, (3) a basic oscilloscope, and (4) a plain sound level meter.

After having determined the headphone terminal voltage corresponding to the average hearing threshold of the reference test subjects, the sound pressure level produced by the headphone driven with exactly the same voltage in an ear simulator or acoustical coupler is measured, see Figure 5.

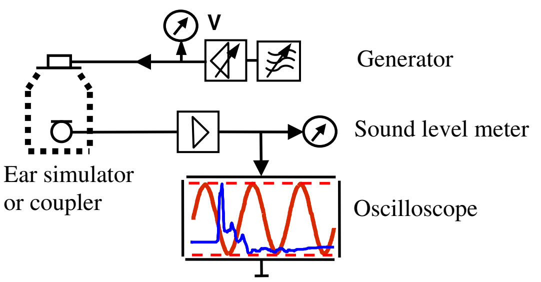


Figure 5. Determination of peak-to-peak equivalent Reference Equivalent Threshold Sound Pressure Levels (peRETSPLs). The generator alternately produces short-term signals and sine waves.

Before the unweighted sound pressure level is read, the short-term signal is replaced by a long-term sinusoidal signal adjusted to the peak-to-peak sound pressure difference of the short-term signal. The sound pressure level of this very sinusoidal signal is the peRETSPL.

On the other hand, when calibrating an audiometer, its output level is adjusted in such a way that the short-term signal produces a peak-to-peak sound pressure – in the ear simulator or coupler specified for the reference threshold – that equals the peak-to-peak sound pressure of a sinusoidal signal with the prescribed peRETSPL value.

Consider two stimuli with identical power spectra, a conventional click signal (a) and a modern chirp signal (b). Figure 6 illustrates that they differ considerably in their peak-to-peak amplitudes of the electrical signals. The chirp, though having the lower peak-to-peak amplitude, causes a higher auditory evoked potential (AEP) [3].

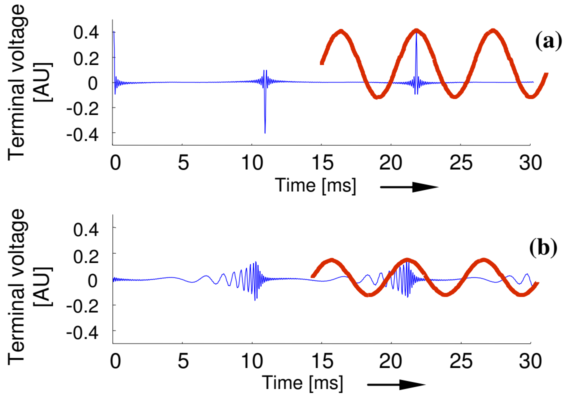


Figure 6. Signals with identical power spectra: headphone terminal voltage, arbitrary units [AU], (a) click, (b) chirp, **bold**: peak-to-peak equivalent sine waves.

Signals with identical headphone terminal voltage power spectra (but different phase spectra), e.g. the two signals shown in Figure 2, have equal (behavioural) reference hearing thresholds when presented with the same conventional audiometric headphone type, as reported in [4]. The peRETSPLs, however, differ widely.

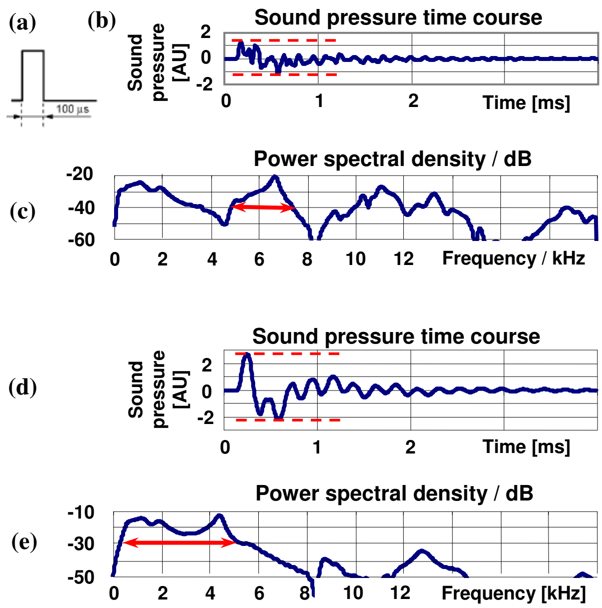


Figure 7. Ear simulator/coupler dependence of peRETSPL. (Arrows: dominant frequency bands, dashed lines: peak-to-peak amplitudes) (a) IEC 60645-3 reference pulse; (b) and (c): IEC 60318-1 ear simulator: 33 dB peRETSPL; (d) and (e): IEC 60318-3 coupler: 39 dB peRETSPL.

PeRETSPL drawbacks

The peRETSPL, since it is strongly dependent on the crest factor of the sound pressure signal measured in the ear simulator or acoustical coupler, lacks - in terms of hearing physiology - coherence with the behavioural hearing threshold. The crest factor essentially depends on both the stimulus waveform, and the response of the audiometric headphone on the ear simulator or acoustical coupler.

Figure 7 shows an example of the measurement of peRETSPLs of reference pulses according to IEC 60645-3 for a typical audiometric headphone. The IEC 60318-1 ear simulator features a narrow-band response (c), whereas the IEC 60318-3 acoustical coupler yields a wide-band response (e), cf. the red arrows in Figure 7 (c) and (e). Thus, these peRETSPLs deviate considerably.

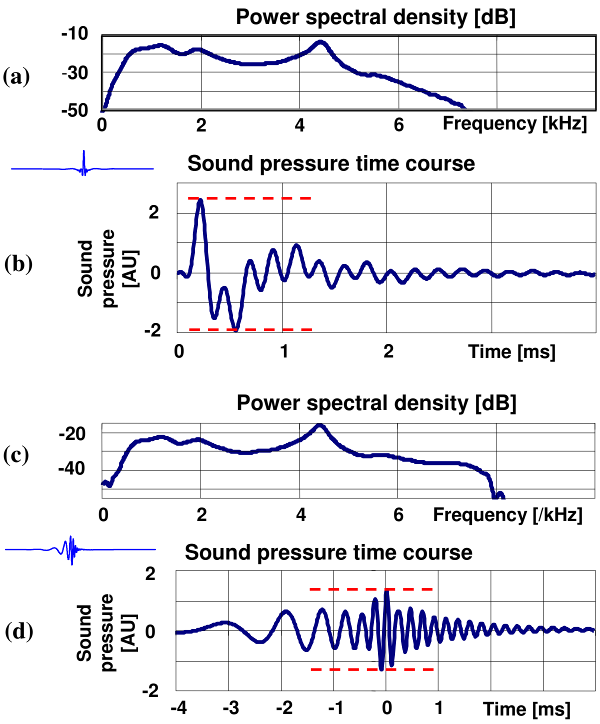
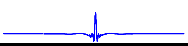
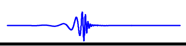


Figure 8. Band limited (200 Hz to 8 kHz) signals with essentially similar power spectra. Dependence of reference value on waveform, measured in IEC 60318-3 acoustical coupler, (a) and (b): click: 38 dB peRETSPL; (c) and (d): chirp: 33 dB peRETSPL. (Note different time scale for (d).)

The dependence of the peRETSPL on the waveform of the stimulus is illustrated in Figure 8. Despite the essentially equal power spectra of the click and the chirp, the peRETSPLs measured by means of an acoustical coupler differ by 5 dB, cf. (b) and (d) in Figure 8.

Furthermore, for the same headphone driven by the same voltage, the reference values measured with the ear simulator and with the acoustical coupler are contradictory: The ear simulator reference value of the chirp is higher than that of the click; for the acoustical coupler, a reversed situation has to be stated, see Table 1.

Table 1. Reference threshold sound pressure levels.

Signals (200 Hz – 8 kHz)	**Ear simulator** IEC 60318-**1**	**Acoustical coupler** IEC 60318-**3**
	**29** *dB peRETSPL*	**38** *dB peRETSPL*
	**32** *dB peRETSPL*	**33** *dB peRETSPL*

Attempts towards a reference value with a physiologically adequate relation to the behavioural hearing threshold

Therefore, for a long time, researchers and development engineers called for a calibration scheme producing reference values with a physiologically adequate relation to the behavioural hearing threshold. A variety of signal characteristics, including r.m.s. value, peak value, and slew rate, turned out to be unsuitable for such an 'intuitive' reference. However, a first step was to simplify the calibration procedure by associating equal reference values to signals having identical power spectra, i.e. classifying them, see Figure 9. This approach is based on the result that such signals yield identical hearing thresholds when presented by ordinary audiometric headphones [4]. For each class, only one signal needs to be acoustically calibrated, provided that the manufacturer guarantees identical power spectra for each class member, e.g. by ROM storage of the signals. The calibration of the class representative can then be performed in the usual way according to ISO 398-6.

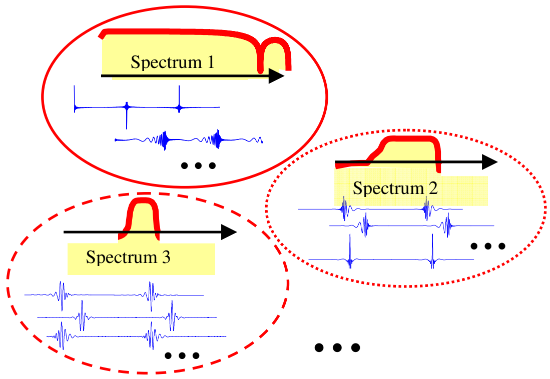


Figure 9. Classification of test signals with identical power spectra. Red: spectra. Blue: waveforms. Only one signal out of each class needs peRETSPL calibration.

CONCLUSIONS

By means of a proposed time-domain tolerance diagram for electrical reference pulses, the discrepancies – due to overshoot and transient oscillations – between the current definition in IEC 60645-3:2007 and practical realizations could be resolved. Though an 'intuitive' single-number acoustical calibration with a physiologically adequate relation to the behavioural hearing threshold still has to be designed, a classification of test signals with identical power spectra helps to reduce the calibration efforts for the variety of short-term signals used in the objective audiometry.

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