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Acoustics — Noise from shooting ranges —

Part 6:
Sound pressure measurements close to the source for determining exposure to sound

Acoustique — Bruit des stands de tir —

Partie 6: Mesurages de la pression sonore près de la source pour déterminer l'exposition au son

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Contents

Page

Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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This document was prepared by Technical Committee ISO/TC 43, *Acoustics*, Subcommittee SC 1, *Noise*.

A list of all parts in the ISO 17201 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

ISO 17201-1 to ISO 17201-5 (see Clause 2 and References [2] to [5]) relate to the determination or prediction of environmentally relevant sound immission at receiving locations outside shooting ranges.

There are countries, where the need exists also for knowledge about exposure to sound within a shooting range at short distances from the sound source, for instance for prediction, evaluation, assessment, control or comparison purposes.

Various methods and metrics are in use for the determination of exposure to impulsive sounds, and these can be derived from the measurement and analysis of the time history of sound pressure at the locations of interest.

Close to the muzzle blast or blast of an explosion, the measurement of sound pressure has particular features to be considered. This document can be applied to both indoor and outdoor shooting ranges that can contain different elements or usage situations. The method is applicable for locations where persons may be present at the shooting range, including the shooter and other persons (such as an instructor, supervisor, bystander or observer). The locations of interest include the position of the shooter (and posture and orientation) and the position of other persons within the shooting range.

This document defines how the time history of the sound pressure at locations of interest within a shooting range, regarding the exposure to impulsive sound of a person, can be reliably obtained.

Acoustics — Noise from shooting ranges —

Part 6:
Sound pressure measurements close to the source for determining exposure to sound

1 Scope

This document specifies methods for recording the time history of the sound pressure produced either by shooting with calibres of less than 20 mm, or by detonation of explosive charges of less than 50 g TNT equivalent, within the shooting range at locations of interest, regarding the exposure to sound of the shooter, or any other person within the shooting range. The time history of the sound pressure can be the basis for further analyses of this type of sound at the locations of interest.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 17201-1:2018, *Acoustics — Noise from shooting ranges — Part 1: Determination of muzzle blast by measurement*

ISO 80000-8, *Quantities and units — Part 8: Acoustics*

IEC 60942, *Electroacoustics — Sound calibrators*

IEC 61094-4, *Measurement microphones — Part 4: Specifications for working standard microphones*

IEC 61094-6:2004, *Measurement microphones — Part 6: Electrostatic actuators for determination of frequency response*

IEC 61672-1:2013, *Electroacoustics — Sound level meters — Part 1: Specifications*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 80000-8 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.or

3.1
discrete-time sound pressure signal series
sound pressure history with values given for discrete times

Note 1 to entry: In general, this time-series is the result of sampling the recorded sound pressure time-history.

Note 2 to entry: In all applications in this document, equal time spacing is assumed.

3.2
sampling
reduction of a continuous-time signal series to a discrete-time signal series

3.3
sample
value at a point in time within a discrete-time signal series

Note 1 to entry: Samples can be in various number formats, typically integer or real.

Note 2 to entry: Scaling and offset information is needed if samples are not stored as sound pressure values.

3.4
sampling interval
T_s
time between two adjacent values in a discrete-time signal series

Note 1 to entry: The sampling interval T_s is expressed in seconds.

3.5
sampling rate
f_s
number of *samples* (3.3) per second

Note 1 to entry: The sampling rate f_s is expressed in hertz.

Note 2 to entry: $f_s = \dfrac{1}{T_s}$.

4 Measurement system requirements

4.1 General

This clause specifies instrumentation for measuring impulsive sounds from the sources specified in the scope. The purpose is to enable the reliable and accurate measurement of sound pressure histories which can be used as input to various methods for describing impulsive sound characteristics such as sound exposure level, peak sound pressure level, A-duration, etc. as for example defined in ISO 10843[1].

As this clause specifies the frequency range and other system requirements, data obtained within the given specifications can be compared to other measurement results obtained using this method.

4.2 Ranges of sound pressure levels

The peak sound pressure level depends, among other things, on the source energy of the blast and the distance to it. At close distances to the source, the peak sound pressure can be above 1 kPa, corresponding to a level above 154 dB. The other parts of ISO 17201 series can only be used for sound pressure levels below 154 dB, since these parts are concerned with sound propagation. This document is focused on the measurement of the time history of the sound pressure; therefore no limit on the peak sound pressure level is set.

4.3 Overall system description

The measurement system shall consist of at least a microphone with a preamplifier and a digital data acquisition system capable of storing digital signals for later retrieval and processing.

The measurement system including the digital data acquisition system shall meet the requirements for the limits on frequency response for Class 1 according to IEC 61672-1:2013, 5.5 using Z-weighting.

NOTE   For the calculation of quantities specified in IEC 61672-1, also see Annex B.

4.4 Microphone and preamplifier requirements

The measurements shall be performed with a pressure type microphone meeting the requirements for a WS3-P or WS2-P microphone as defined in IEC 61094-4. The use of a WS3-P microphone is preferred, since the influence of the angle of incidence within the frequency range of interest is smaller compared to a WS2-P microphone.

NOTE 1   A microphone of type WS3-P is often named ¼ inch working standard pressure microphone and WS2-P a ½ inch working standard pressure microphone.

The microphone shall be connected to a cylindrical preamplifier with a diameter not larger than that of the microphone. The microphone and preamplifier combination shall have the capability to measure peak sound pressure levels in the appropriate range, with

$$L_{p,\mathrm{max}} \le L_{p,\mathrm{OL}} - 5\,\mathrm{dB} \tag{1}$$

where

$L_{p,\mathrm{max}}$ is the peak sound pressure level to be measured, expressed in decibels;

$L_{p,\mathrm{OL}}$ is the maximum peak sound pressure level at which the microphone and preamplifier combination is not overloaded, expressed in decibels

and $L_{p,\mathrm{nf}} \le L_{p,\mathrm{max}} - 60\,\mathrm{dB}$ (2)

where $L_{p,\mathrm{nf}}$ is the A-weighted noise floor of the microphone and preamplifier combination, expressed in decibels.

NOTE 2   The A-weighted noise floor is used because this value is typically specified in microphone and preamplifier data sheets.

A microphone and preamplifier combination capable of measuring peak sound pressure levels of at least 165 dB is recommended.

The dynamic range of the microphone and preamplifier combination shall be at least 100 dB. The dynamic range is the range from the highest peak sound pressure level capacity of the microphone to the A-weighted noise floor level of the microphone and preamplifier combination.

The frequency response of the microphone and preamplifier shall be calibrated with an electrostatic actuator according to IEC 61094-6 in the frequency range from 250 Hz to 20 kHz. This calibration shall be performed less than 365 days before the measurements. This is defined in IEC 61094-4:2004, Figure 2 and Table 2.

NOTE 3   The calibration according to IEC 61094-6 is usually performed by the microphone manufacturer or a calibration laboratory.

4.5 Microphone fixture

A fixture with small influences on the measured sound field shall be used for the preamplifier and microphone to reduce influences of the fixture on the measured sound field.

4.6 Cable length

The microphone and preamplifier shall be capable of handling the occurring signal rise times. The signal rise time handling capacity is often determined by the preamplifier and the capacity of the cable between the preamplifier and data acquisition system. If the cable length is increased, the cable capacity increases and the signal rise time handling capacity of the system decreases. It is therefore important to ensure that the signal rise time handling capacity is determined for the actual cable length used in

the setup. For more information about slew rate limitations and signal rise time handling capacity, see Annex A.

NOTE   In many microphone and preamplifier combinations, the limiting factor for the high peak sound pressure handling capacity is the preamplifier, rather than the microphone.

4.7   Wind screens

It is recommended to perform measurements without a windscreen, because windscreens will change the high frequency content of the signal and may affect the measured peak values.

However, even moderate wind speeds may cause significant wind induced noise signals from the microphone and it is therefore recommended to check the residual noise during the measurements. If the difference between the peak C-weighted sound pressure level during the 3 s before the impulsive sound event and the measured C-weighted peak sound pressure value during the impulsive sound event is less than 60 dB, the use of a windscreen is recommended. For series of measurements of impulsive sound events with less than 3 s in between, the level of the residual background noise only needs to be measured once.

4.8   Data acquisition system

The data acquisition system shall have a sample rate of at least 96 000 samples per second and shall be able to store at least 10 s of continuous data. The resolution of the data acquisition system shall be at least 20 bit.

The data acquisition system shall be equipped with an anti-aliasing filter attenuating all signal components above the Nyquist-frequency $f_s /2$.

For frequencies from $f_s /2$ and higher, the attenuation shall be at least 10 dB.

The attenuation of the anti-aliasing filter shall be verified either by measurement or by using the technical specifications provided by the manufacturer.

4.9   Data storage

The recorded discrete-time sound pressure signal series shall be stored in a digital file format, uncompressed or with lossless compression. It can be stored directly as a discrete-time sound pressure signal series, or as a sampled data time-series. In the latter case, calibration factor and offset information shall be provided additionally. In both cases, timing information shall be provided to link each sample or data point to time.

If sampled data time-series are stored, the WAV-Format may be used, for example.

Timing information shall be provided either by giving the time for each data point or by giving the sampling rate and the time of the first sample.

4.10 Frequency-weighting

All data shall be recorded and stored with Z-weighting given in IEC 61672-1.

4.11 Field calibration

The field calibration of the system shall include the response of the microphone, preamplifier, all cables and the data acquisition system. The calibration shall be performed at either 250 Hz or 1 kHz, at a minimum sound pressure level of 114 dB, using a sound calibrator Class 1 as defined in IEC 60942. The calibration shall be performed before the measurements and again after the measurements, not earlier than two hours before the measurements and not later than two hours after the measurements.

The calibration before the measurement may include an adjustment of sensitivity parameters. The calibration after the measurement is a verification of calibration conformance.

The calibration, including differences between first and second calibration, shall be documented, and this documentation shall be included with the measurement documentation.

5 Measurement setup

5.1 General considerations

The measured time history of the sound pressure from a specific weapon or explosive charge is influenced by the acoustical environment within the specific shooting range. Any reflections and scattering from the ground, walls or other obstacles as well as effects due to the presence of persons are included in the measurement. For a specific weapon the result may also depend on the directivity of the sound radiation from the weapon and the location and posture of the shooter.

The sound pressure at the ears of a person at a location of interest can be very different for the left and right ear, and is influenced by specific details such as different head shapes and the exact orientation of the head. Measurement setups that take all these influences into account typically provide results for very individual events.

To enable generic and reproducible measurement results, the measurements are therefore carried out without the presence of the person at the location at which the exposure to sound is to be determined, and the microphone is placed where the centre of the head of that person would be.

5.2 Measurement location

To determine the exposure to sound at a location of interest

— within a specific shooting range,

— for a specific body posture, and

— for a specific source (firearm or explosive charge),

measurements are performed with a person at that location being absent, and the microphone placed where the centre of the head would be.

5.3 Special case: Weapons fixture

To determine the exposure to sound at the location of a shooter discharging a firearm, the shooter is absent, and the weapon is placed in a fixture and operated remotely. Only in this special case the measurement of shooting sound shall be performed in the absence of the shooter. The microphone is placed in the position where the centre of the head of the shooter would be.

The weapons fixture shall be constructed in such a way that the sound reflected by the fixture does not contribute significantly to the recorded discrete-time sound pressure signal series.

5.4 Persons in the shooting range

The presence of persons in the shooting range can influence the exposure to sound at the location of interest. As an example, if the location of interest is behind the shooter, the head and body of the shooter is expected to significantly influence the exposure to sound at that location. Another example would be a person between the blast source and the location of interest.

If the presence of persons in the shooting range is deemed to influence the exposure to sound at the location of interest, the measurements shall be performed with these persons present. Therefore, if measurements are performed in regard to a firearm, the shooter is always present if the location of interest is not the location of the shooter itself.

5.5 Simultaneous multi-location measurements

Simultaneous measurements are allowed if, for the locations of interest, the presence of a person (other than the shooter) is not deemed to influence the exposure to sound at these measurement locations. This means that if the location of a shooter as well as the location of bystanders is of interest, two separate measurement series should be performed, one without the shooter for this location and a second with the shooter present but without persons present at the other locations of interest.

5.6 Exception: Absence of persons influencing the exposure to sound

Single and multi-location measurements in the absence of a person or persons which might, when present, influence the exposure to sound at the measurement locations are allowed, but require a clear and prominent statement in the documentation.

5.7 Microphone orientation

The microphone shall be mounted vertically, with the diaphragm facing upwards.

NOTE   In terms of IEC 61672-1, the reference direction is vertical.

5.8 Weather and ambient conditions

There are no restrictions for weather and ambient conditions. It is recommended to make measurements not likely to be affected by precipitation and or high wind conditions.

6 Documentation

6.1 General

A general description of the measurement system and the layout shall be given together with a brief explanation of the purpose of the measurement.

6.2 Shooting range

A schematic diagram of the shooting range shall be given. The diagram shall include indications that show the firing position of the weapon or explosive charge and positions of all persons for which the exposure of sound is to be determined as well all other persons relevant to the measured sound pressure.

6.3 Absorbing and reflecting elements

For elements such as the ground, walls, baffles and barriers which are part of the shooting range, a description of the materials thereof shall be documented with a statement as to their sound absorbing and reflecting properties.

6.4 Sound source documentation

Documentation of the firearm and ammunition or of the explosive charge shall be given as specified in ISO 17201-1:2018, Clause 4. If projectile sound is measured, physical dimensions and ballistic data of the projectile shall be documented.

6.5 Location of the primary source of the sound

The position of the sound source shall be clear from the schematic diagram of the shooting range or given in the text of the report. In the case that measurements are performed in regard to shooting sound the shooting direction and the height of the muzzle shall be stated. If the elevation of the firearm

is larger than five degrees or smaller than minus five degrees, the elevation shall also be given in the report.

The centre of the muzzle blast is generally located at some distance in front of the muzzle. If this location is known, or there is an estimate for it, such information shall be given in the report.

6.6 Shooter

In the case that measurements are performed in regard to shooting sound, it shall be stated whether the firearm is operated by a shooter or remotely operated and in a fixture.

The location and posture of the shooter (standing, kneeling, sitting, prone) and the left or right handed use of the firearm shall be documented.

If a weapons fixture is used, it is mandatory that the used fixture be extensively documented.

6.7 Measurement location

The measurement location shall be specified. For the microphone, the height of the diaphragm shall be reported.

If measurements are taken at several locations at the same time, each measurement location shall be reported.

6.8 Weather and ambient conditions

The weather and ambient conditions shall be reported. These include at least:

— temperature;

— barometric pressure;

— humidity.

If the measurement is performed outside or inside a partial enclosure of the shooting range, the following weather information shall also be reported:

— presence and type of precipitation;

— wind speed and direction, including the height at which these values are determined.

7 Data evaluation and uncertainties

7.1 General

While this document does not provide an evaluation or assessment of the time history of the sound pressure, further information on how to use the sound pressure time series is given in this clause.

7.2 Evaluating discrete time data

Some evaluation schemes require the calculations of quantities that are given as an integral of a function of the sound pressure over time. A guideline on how to replace the integral with a sum and how to work with a discrete sound pressure time series is given in Annex B.

7.3 Frequency-weighting

If A- or C-weighting are applied to the Z-weighted sound pressure time series for evaluation or assessment of the data, filters as specified in IEC 61672-1:2013, Annex E, shall be used. For further information on C-weighting in the time domain, see Annex C.

7.4 Measurement uncertainties

There are several possible sources for the measurement uncertainties that result in an uncertainty for the measured sound pressure time series for the same measurement setup, i.e. the same sound source, at the same location within the same shooting range. Possible sources for uncertainties in the measurement of sound pressure time histories due to the measurement setup and conditions are:

— variations in the source signal;

— background noise;

— uncertainties in sensitivity and directional dependency of the microphone;

— calibration of instrumentation;

— reflections and scattering from the microphone fixture;

— variations in wind screens (if used);

— reflections and scattering from the weapon fixture (if used);

— reflections and scattering from persons nearby the measurement location dependent of the size, clothing and posture of those persons;

— location of microphone, source and bystanders;

— electromagnetic interference;

— changes in atmospheric conditions;

— shape, dimension, packaging and positioning (attachment) of explosive.

For the measurement of multiple sound pressure histories of a muzzle blast or blast from an explosion, variations in the shape of the sound pressure histories must be expected.

There is no appropriate way to take several recordings of impulsive sound, and to form an average signal. The variations between the signals might just be what is important for the assessment of the exposure to sound. Using some kind of an averaged time history of the sound pressure could result in errors for such assessment.

In many cases, quantities like C-peak, sound exposure level or ARU (auditory risk unit, see Reference [8]) are calculated for the assessment. In these cases, the measurement uncertainties for the calculated quantities shall be evaluated, preferably in accordance with ISO/IEC Guide 98-3.

Annex A
(informative)

Slew rate limitations for impulse sound measurements

Slew rate limitations in the measurement system can prevent the proper measurement of impulsive signals. This is especially pronounced when using long cables. Slew rate limitations are most often caused by microphone preamplifiers, but can also be caused by other parts of the measurement equipment.

For the case of microphone preamplifiers, the limitation is associated with the ability of the preamplifier to deliver current to drive the capacitance of the cable connected to the output of the preamplifier. Typical preamplifier cables have a capacitance of 50 pF/m to 100 pF/m, therefore a 25 m cable connected to the preamplifier represents a capacitive load of 1,25 nF to 2,5 nF.

If the microphone detects a sudden change of pressure, for example from a gunshot, this input signal is converted to a corresponding voltage signal into the preamplifier. The conversion rate is given by the microphone sensitivity in volts per Pascal.

The slew rate limitation in a given preamplifier can be different for positive and negative going signals. As an example, a positive going impulse is considered, which can be modelled as a step function going from 0 Pa to for example 10 000 Pa (corresponding to 174 dB) very rapidly as indicated in Figure A.1.

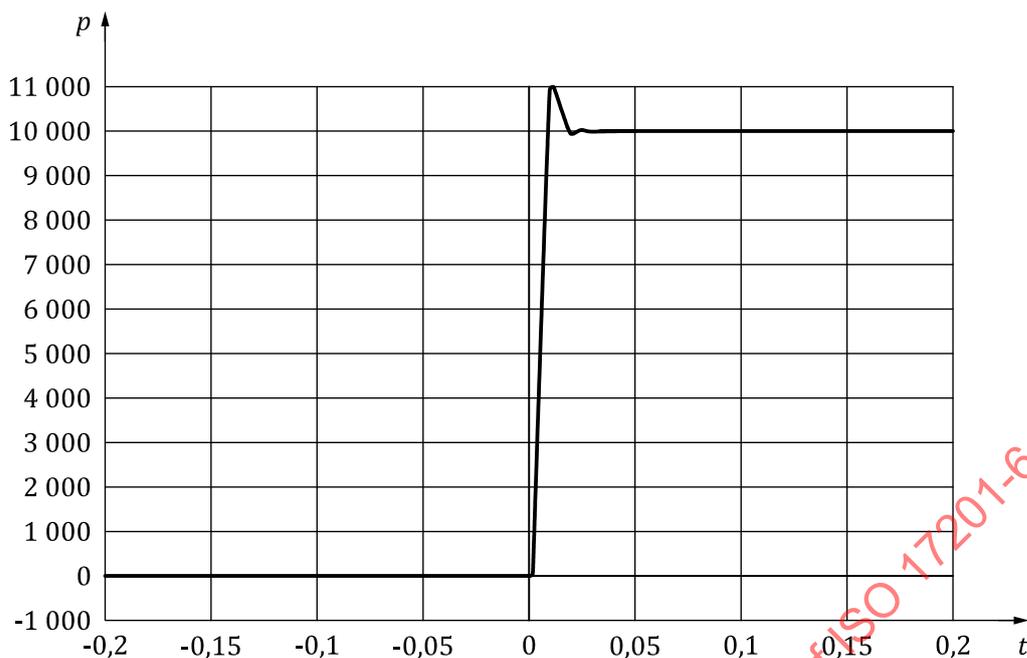**Key**
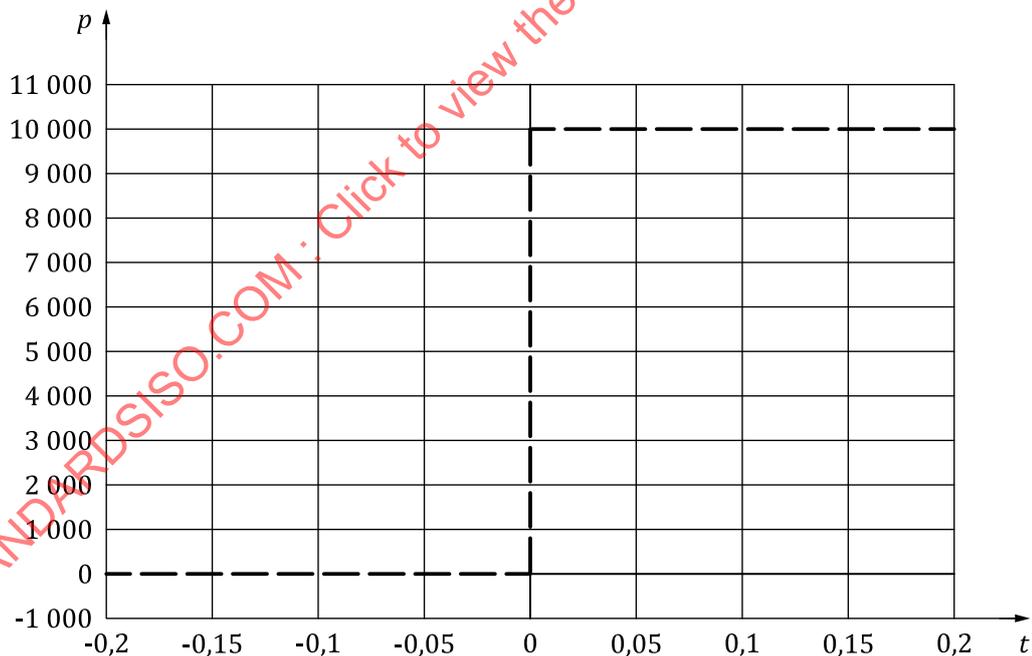
t time, expressed in milliseconds

p sound pressure, expressed in Pascals

Figure A.1 — Ideal step impulse, 10 000 Pa

Due to the finite frequency range of the microphone, the microphone is not able to respond perfectly to the step function, but has a certain response time resulting in a signal as indicated in Figure A.2.
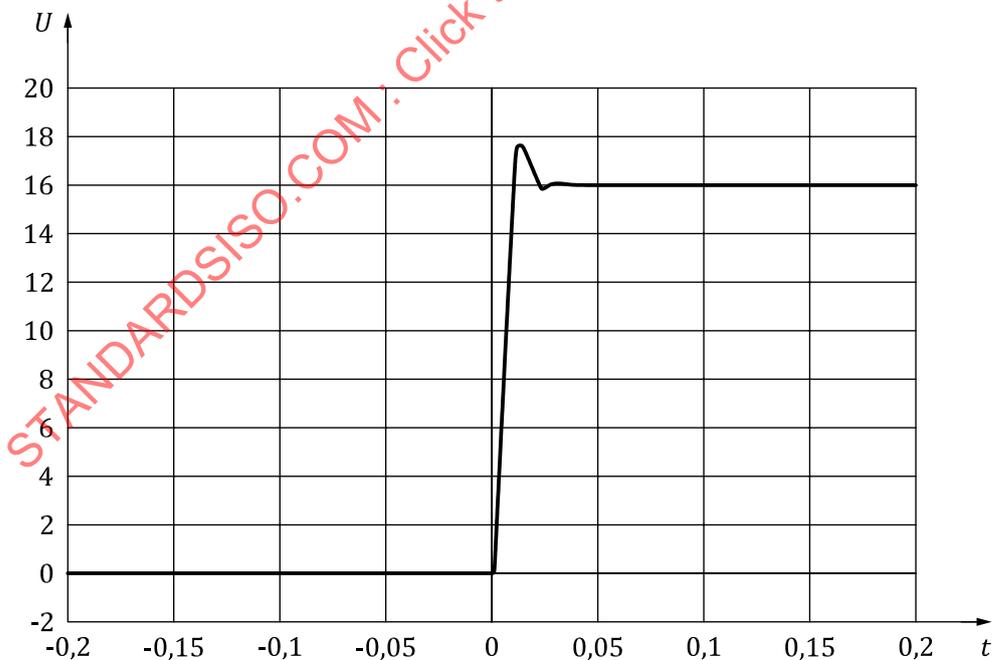
Key

t time, expressed in milliseconds

p sound pressure, expressed in Pascals

Figure A.2 — Microphone signal with 40 kHz band limiting

For a typical microphone with a sensitivity of 1,6 mV/Pa, the output signal from the microphone into the preamplifier is as seen in Figure A.3.


Key

t time, expressed in milliseconds

U voltage, expressed in volts

Figure A.3 — Microphone output voltage

The preamplifier has to pass this signal through the cable attached to the A/D converter or analyzer input. Figure A.4 shows a simple model of this system, with the preamplifier modelled as a voltage source, S_U, the cable capacitance C_c, the current, I, generated by the voltage source and the voltage, U_{out}, as measured by the analyzer or A/D converter.
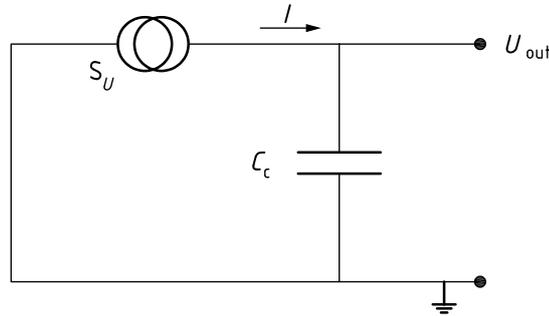
Key

S_U voltage source

I current

U_{out} output voltage

C_c cable capacitance

Figure A.4 — Simple model of preamplifier output and cable capacitance

In order for the output signal U_{out} to accurately follow the input signal to the preamplifier, the voltage source S_U has to charge the capacitance C_c. The output current, from the voltage source i, can be calculated according to Formula (A.1):

$$I = C_c \frac{dU}{dt}$$

(A.1)

where

I is the current, expressed in amperes;

C_c is the capacitance, expressed in farads;

U is the output voltage from voltage source, expressed in volts;

t is the time, expressed in seconds.

Assuming the preamplifier is connected to a 25 m cable with 100 pF/m capacitance, giving a total capacitance of 2,5 nF, the current can be calculated as shown in Figure A.5.

Key
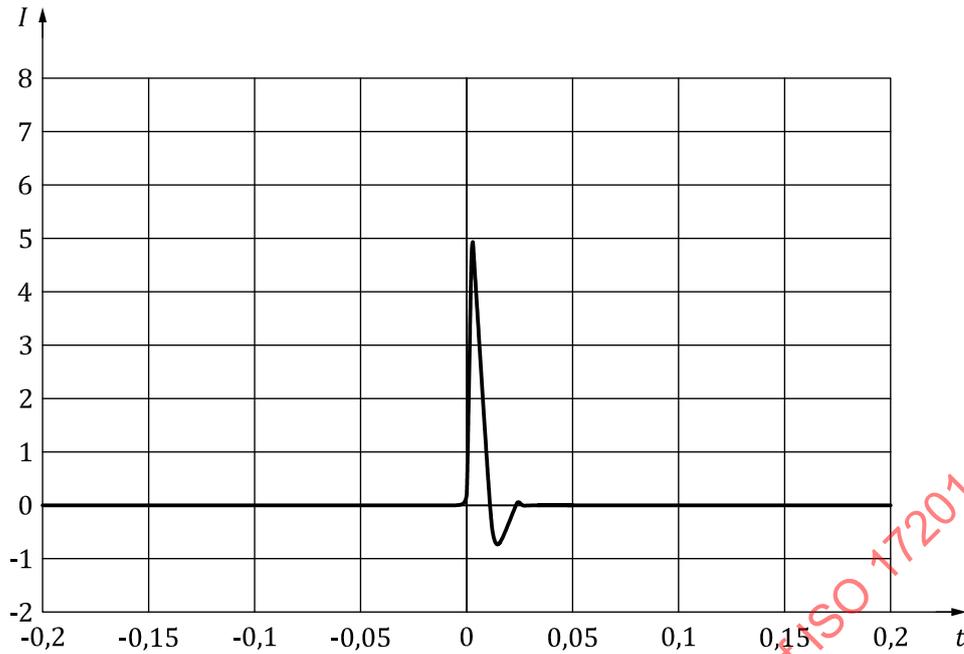
t time, expressed in milliseconds

I current, expressed in milliamperes

Figure A.5 — Preamplifier current to drive 25 m cable

It can be seen that the maximum current is around 5 mA and this is what is required for the preamplifier to deliver in order to reproduce the signal from the microphone. If the preamplifier can only deliver for example 2 mA, the signal is slew rate limited. The signal is heavily distorted and it is not possible afterwards to reconstruct the original signal. It is important to note that the distortion is not a linear filtering process or band limiting effect, but a fully non-linear distortion.

The current capability of a preamplifier depends on the actual implementation of the preamplifier and the supply voltage and current to the preamplifier. Typical preamplifiers can have a maximum output current in the range from 1 mA to 4 mA, and it is important not to exceed this capability.

It should also be noted that the preamplifier current handling capacitance can be different for positive and negative going signals. As externally polarized microphones traditionally give a negative voltage output for a positive sound pressure input, the preamplifier signal can be an initially negative going signal and the preamplifier output current is negative.

The results in Figure A.5 are for the specific combination of a microphone with 1,6 mV/Pa sensitivity and 40 kHz bandwidth, a 25 m cable with a capacitance of 100 pF/m and a 10 000 Pa step function input.

A step function is unlikely to occur during practical measurements, but can be used as a worst-case signal. Practical signals have a finite rise time and therefore the microphone output signal is determined by either the signal itself or by the microphone bandwidth.

For the microphone, the two important factors are the sensitivity and the bandwidth. If the sensitivity is increased, the required current increases proportionally. If the sensitivity is 50 mV/Pa instead of 1,6 mV/Pa, the required current in the specific example above with a 10 000 Pa step input goes up 31,25 times from 5 mA to 156 mA.

The voltage change per time unit for the microphone output signal depends on the bandwidth of the transducer. If the bandwidth of the microphone with 1,6 mV/Pa sensitivity is 20 kHz instead of 40 kHz, the current goes down to about 2,5 mA instead of the 5 mA, and the requirements for the preamplifier can be reduced.

Annex B
(informative)

Calculations with discrete-time data

B.1 General

Many definitions for calculations of key values like sound exposure are based on integrals. For calculations with discrete-time sound pressure series, these calculations are replaced using sums instead of integrals.

Assume a formula for the continuous time sound pressure signal:

$$F_c = \int_{t_1}^{t_2} f[p(t)]dt \tag{B.1}$$

where

F_c is the result of the integration;

f is some function of the sound pressure signal;

$p(t)$ is sound pressure at time t, expressed in Pascals;

t_1 is the start of the time window, expressed in seconds;

t_2 is the end of the time window, expressed in seconds.

For the discrete-time series, Formula (B.1) is replaced by Formula (B.2):

$$F_d = T_s \sum_{k \in \mathcal{K}} f(p_k) \tag{B.2}$$

where

F_d is the result of the summation;

k is the index for the time-domain;

$\mathcal{K}$ is the set of indices k with $t_1 \le t_k \le t_2$;

p_k is element k in the discrete-time sound pressure series, expressed in Pascals;

T_s is the sampling time, expressed in seconds.

B.2 Example: exposure calculation

For example, the sound exposure is calculated as given in Formula (B.3):

$$E_{T,c} = \int_{t_1}^{t_2} p^2(t)dt \rightarrow E_{T,d} = T_s \sum_{k \in \mathcal{K}} p_k^2 \tag{B.3}$$

where

13

$E_{T,c}$ is the sound exposure calculated from the continuous time signal, expressed in Pascals square seconds;

$E_{T,d}$ is the sound exposure calculated from the discrete time series, expressed in Pascals square seconds;

k is the index for the time-domain;

$\mathcal{K}$ is the set of indices k, with $t_1 \leq t_k \leq t_2$;

p_k is element k in the discrete-time sound pressure series, expressed in Pascals;

$p(t)$ is the recorded sound pressure signal at the time, t, expressed in Pascals;

t_1 is the start of the time window, expressed in seconds;

t_2 is the end of the time window, expressed in seconds.

Annex C
(informative)

Calculating C-weighted time series using a digital filter

C.1 General

Often measurements are available as sampled time series. To determine derived quantities from such a series, for example a C-weighted peak level, there is a need for a C-weighted time series. This annex describes how such a C-weighted time series can be determined using a digital filter.

C.2 C-weighting characteristic

In IEC 61672-1:2013, Annex E, the C-weighting characteristic function is given by Formula (C.1):

$$C(f) = 10\lg\left(\frac{f_4^2 f^2}{\left(f^2 + f_1^2\right)\left(f^2 + f_4^2\right)}\right)^2 \text{dB} - C_{1\ 000} \tag{C.1}$$

where

f is the frequency, expressed in hertz;

f_1 is the low frequency pole, expressed in hertz;

f_4 is the high frequency pole, expressed in hertz;

$C_{1\ 000}$ is the normalization constant, expressed in decibels.

This frequency response can be realized with a low-pass (LP) and a high-pass (HP) first order Butterworth filter, both applied twice. The low-pass and high-pass Butterworth filters can be described in the s-domain by:

$$G_{\text{LP}} = \frac{1}{1 + s/\omega_4} \tag{C.2}$$

$$G_{\text{HP}} = \frac{s}{s + \omega_1} \tag{C.3}$$

The frequency response of the C-weighting filter can then be described by:

$$H_{\text{C}}(s) = G_{\text{C}} G_{\text{LP}}^2 G_{\text{HP}}^2 \tag{C.4}$$

$$H_{\text{C}}(s) = G_{\text{C}} \frac{\omega_4^2 s^2}{\left(s + \omega_1\right)^2 \left(s + \omega_4\right)^2} \tag{C.5}$$

Formula (C.5) can also be found in the definition for the C-weighting filter in ANSI S1.42[7]. The frequencies are given as f_1 = 20,98997 Hz and f_4 = 12 194,217 Hz (with ω_n = 2πf_n), and G_{C} is the normalization constant, required to make the frequency response equal to 0 dB at 1 000 Hz. This normalization constant is defined in IEC 61672-1 as G_{C} = $10^{0,062/20}$ = 0,062 dB. Formula (C.1) can be

derived from Formula (C.5) by replacing s by $i\omega$, ω by $2\pi f$ and calculating the frequency magnitude response with Formula (C.6):

$$C(f) = 10\lg\left[H_C(s)H_C^*(s)\right]$$ (C.6)

C.3 Derivation of the digital filter using the bilinear transform

The analogue filter defined in Formula (C.5) can be transformed to a digital filter using the bilinear transform. With such a digital filter it is then possible to directly calculate the response $y[n]$ of the C-weighting filter on a sampled time signal $x[n]$. No Fourier-transforms are necessary; all calculations can be performed in the time-domain. The digital filter is an IIR filter (having an infinite impulse response) of the form given in Formula (C.7).

$$y[n] = \frac{1}{a_0}\left[\sum_{j=0}^{N}b_j x[n-j] - \sum_{k=1}^{M}a_k y[n-k]\right]$$ (C.7)

The coefficients a_k and b_j from Formula (C.7) can be derived from Formula (C.5) by the use of a bilinear transform in which the continous s-domain transfer function of Formula (C.5) is transformed to the discrete Z-domain by replacing s in Formula (C.5) by using Formula (C.8):

$$s \rightarrow \frac{2}{T_s}\frac{\left(1-z^{-1}\right)}{\left(1+z^{-1}\right)}$$ (C.8)

where

z is the Z-transform ($z = e^{T_s s}$);

T_s is the sampling interval, expressed in seconds.

This leads to a formula having the general form of Formula (C.9). Therefore, using the bilinear transform, the parameters a_k and b_j can be expressed in terms of ω_1 and ω_4.

$$H(z) = \frac{\sum_{j=0}^{N}b_j z^{-j}}{\sum_{k=0}^{M}a_k z^{-k}}$$ (C.9)

There is a however a non-linear relationship between the analogue frequency and the digital frequency. Therefore, a last step is necessary in which in the relations for the coefficients a_k and b_j of Formula (C.7), ω_1 and ω_4 are replaced by the normalized frequencies ω_1' and ω_4' (called frequency warping or pre-warping) using:

$$\frac{\omega_n'}{2f_s} = \tan\left(\frac{\omega_n}{2f_s}\right)$$ (C.10)

where

f_n is the cut-off frequency, expressed in hertz;

f_s is the sampling rate, expressed in hertz.