IEC TS 61400-11-2

Edition 1.0 2024-03

TECHNICAL SPECIFICATION

colour inside

Wind energy generation systems –
Part 11-2: Acoustic noise measurement techniques – Measurement of wind turbine sound characteristics in receptor position

IEC TS 61400-11-2:2024-03(en)

IEC Secretariat
3, rue de Varembé
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
info@iec.ch
www.iec.ch

IEC TS 61400-11-2

Edition 1.0 2024-03

TECHNICAL SPECIFICATION

colour inside

Wind energy generation systems –
Part 11-2: Acoustic noise measurement techniques – Measurement of wind turbine sound characteristics in receptor position

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 27.180

ISBN 978-2-8322-8405-6

Warning! Make sure that you obtained this publication from an authorized distributor.

CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

WIND ENERGY GENERATION SYSTEMS –

Part 11-2: Acoustic noise measurement techniques – Measurement of wind turbine sound characteristics in receptor position

FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
2) The formal decisions or agreements of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees.
3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.
4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.
5) IEC itself does not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC marks of conformity. IEC is not responsible for any services carried out by independent certification bodies.
6) All users should ensure that they have the latest edition of this publication.
7) No liability shall attach to IEC or its directors, employees, servants or agents including individual experts and members of its technical committees and IEC National Committees for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC Publication or any other IEC Publications.
8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.
9) IEC draws attention to the possibility that the implementation of this document may involve the use of (a) patent(s). IEC takes no position concerning the evidence, validity or applicability of any claimed patent rights in respect thereof. As of the date of publication of this document, IEC had not received notice of (a) patent(s), which may be required to implement this document. However, implementers are cautioned that this may not represent the latest information, which may be obtained from the patent database available at https://patents.iec.ch. IEC shall not be held responsible for identifying any or all such patent rights.

IEC TS 61400-11-2 has been prepared by IEC technical committee 88: Wind energy generation systems. It is a Technical Specification.

The text of this Technical Specification is based on the following documents:

Draft	Report on voting
88/995/DTS	88/1009/RVDTS

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this Technical Specification is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

A list of all parts in the IEC 61400 series, published under the general title *Wind energy generation systems*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn, or
- revised.

IMPORTANT – The "colour inside" logo on the cover page of this document indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

INTRODUCTION

The primary objective of this document is to establish uniform measurement and data analysis techniques to facilitate the evaluation of the A-weighted sound pressure level, or other acoustical properties, attributable to wind turbines at representative far-field locations. While this is a seemingly simple objective, wind turbines require wind to operate and the presence of wind complicates reliable acoustical measurements, either directly through wind induced microphone noise or indirectly through wind induced vegetative rustling sound. The presence of other common environmental sounds (planes, trains, road traffic, industrial, agricultural activities, etc.) can complicate or adversely influence the measured sound level. Owing to the distance of sound propagation, the meteorological conditions have a significant impact on the measurement results and the influence should be considered.

Given that the regulatory requirements and history vary from country to country (and even within the same country), this document does not dictate regulatory metrics, but provides guidance on how best to isolate the sound attributable to wind turbines alone in the presence of other environmental sounds. It also provides guidance for those whose regulatory history for wind or other sources require the evaluation of specific acoustical aspects that have historically been subject to highly varying methodologies. Some countries have substantial experience with wind turbines while other countries are new to the special requirements of wind turbine sound measurements. Both can find guidance on how to standardise their approaches.

In general, the document can be used by regulators and authorities, measurement laboratories, developers, operators and manufacturers for

- comparison with local regulation;
- comparison with guarantee values;
- where no tradition for regulations of wind turbine sound immissions is available it can be used to aid the decision process;
- assessment of the sound characteristics in wind turbine sound as well as the sound level.

WIND ENERGY GENERATION SYSTEMS –

Part 11-2: Acoustic noise measurement techniques – Measurement of wind turbine sound characteristics in receptor position

1 Scope

This part of IEC 61400-11 presents measurement procedures, that enable the sound characteristics of a wind turbine to be determined at receptor (immission) locations. This involves using measurement methods appropriate to sound immission assessment at far-field locations of a wind turbine or wind farm. The procedures described are different in some respects from those that would be used for noise assessment from other industrial sound sources in environmental noise impact assessments. They are intended to facilitate characterization of wind turbine sound with respect to a range of wind speeds and directions.

The procedures present methodologies that will enable the sound immission and sound characteristics of wind turbines to be described in a consistent and accurate manner. These procedures include the following aspects:

- location of acoustic measurement positions (receptor position);
- requirements for the acquisition of acoustic, meteorological, and associated wind turbine operational data;
- analysis of the data obtained and the content for the data report; and
- definition of specific acoustic parameters, and associated descriptors which are used for making environmental assessments.

This document is not restricted to wind turbines of a particular size or type. The procedures described in this document allow for the thorough description of the sound characteristics and sound immissions from wind turbines.

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.

IEC 60942, *Electroacoustics – Sound calibrators*

IEC 61400-11:2012, *Wind turbines – Part 11: Acoustic noise measurement techniques*
IEC 61400-11:2012/AMD1:2018

IEC 61400-12-1, *Wind energy generation systems – Part 12-1: Power performance measurements of electricity producing wind turbines*

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

ISO 1996-2:2017, *Acoustics – Description, measurement and assessment of environmental noise – Part 2: Determination of sound pressure levels*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

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

- IEC Electropedia: available at https://www.electropedia.org/
- ISO Online browsing platform: available at https://www.iso.org/obp

3.1
apparent sound power level
L_{WA}
A-weighted sound power level re. 1 pW of a point source at the rotor centre with the same emission in the downwind direction as the wind turbine being measured, L_{WA} is determined at bin centre wind speeds at hub height as described

Note 1 to entry: Apparent sound power level is expressed in dB re. 1 pW.

[SOURCE: IEC 61400-11:2012, 3.1]

3.2
apparent sound power level with reference to wind speed at 10 m height
$L_{WA,10m}$
A-weighted sound power level re. 1 pW of a point source at the rotor centre with the same emission in the downwind direction as the wind turbine being measured, $L_{WA,10m}$ is determined at integer wind speeds at 10 m height within the wind speed range achieved during measurements

Note 1 to entry: Apparent sound power level with reference to wind speed at 10 m height is expressed in dB re. 1 pW.

[SOURCE: IEC 61400-11:2012, 3.2, modified – "achieved during measurements has been added to the definition.]

3.3
A-weighted sound pressure level
L_A
sound pressure level measured with the A frequency weighting networks as specified in IEC 61672-1

Note 1 to entry: A-weighted sound pressure level is expressed in dB re. 20 μPa.

3.4
bin centre
centre value of a wind speed bin or wind direction bin

3.5
time-weighted and frequency-weighted sound pressure level
ten times the logarithm to the base 10 of the ratio of the time-mean-square of the sound pressure to the square of a reference value, being obtained with a standard frequency weighting and standard time weighting

Note 1 to entry: Sound pressure is expressed in pascal (Pa).

Note 2 to entry: The reference value is 20 μPa.

Note 3 to entry: Time-weighted and frequency-weighted sound pressure level is expressed in decibels (dB).

Note 4 to entry: The standard frequency weightings are A-weighting and C-weighting as specified in IEC 61672-1, and the standard time weightings are F-weighting and S-weighting as specified in IEC 61672-1

3.6
background sound
contribution from all sources of acoustic sound other than the source of interest (i.e. wind turbine)

3.7
total sound
totally encompassing sound composed of sound from many sources near and far (including background sound and sound source of interest)

3.8
low frequency sound
sound containing frequency components of interest within the range generally covering the 1/3-octave bands 10 Hz to 200 Hz

Note 1 to entry: This definition is specific for this document. Other definitions can apply in different national regulations.

3.9
tonality
ΔL_k
difference between the tone level and the level of the masking noise in the critical band around the tone in each wind speed bin where k is the centre value of the wind speed bin

3.10
tone frequency
f_T
frequency of the spectral line (or mid band frequency of the narrow band filter), to the level of which the tone contributes most strongly

3.11
tone level
L_T
energy summation of the narrow-band level with the tone frequency, f_T, and the lateral lines about f_T, assignable to this tone

Note 1 to entry: If the critical band for the frequency, f_T, under consideration contains a number of tones, then the tone level, L_T, is the energy sum of these tones. This level, L_T, is then assigned to the frequency of the participating tone that has the maximal value of audibility, ΔL.

3.12
audibility
ΔL
difference between the tonality and the audibility criterion, a_V in each wind speed bin

Note 1 to entry: Tonal audibility is expressed in dB.

3.13
bandwidth
frequency range of a number of neighbouring spectral lines

Note 1 to entry: If the width of a frequency band is calculated, for which its beginning or end does not correspond to the boundary between two spectral lines, then only the spectral lines that lie in their full width within the calculated frequency range are assigned to the frequency band.

3.14
sampling frequency
f_S
number of samples taken per second

3.15
block length
N
block of sampling values that in discrete form represents a time-limited range of the time signal to be analysed

3.16
line spectrum
narrow-band spectrum
frequency spectrum
plot of sound pressure level as a function of the frequency in the frequency bands of constant bandwidth

3.17
line spacing
frequency resolution
distance between neighbouring spectral lines where the line spacing in the fast Fourier transform (FFT) is given by

$$\Delta f = f_S / N$$

where

f_S is the sampling frequency

N is the block length

3.18
critical band
frequency band with a bandwidth, Δf_c, within which the auditory system integrates the sound intensity in the formation of loudness and within which it integrates the sound intensity in the formation of the masking threshold

3.19
mean narrow-band level of the critical band
L_s
energy mean value of all narrow band levels in a critical band that (as a rule) does not exceed this value by more than 6 dB

3.20
audibility criterion
a_v
frequency dependent criterion curve determined from listening tests, and reflecting the subjective response of a 'typical' listener to tones of different frequencies

Note 1 to entry: Audibility criterion is expressed in dB re. 20 μPa.

3.21
critical band level
L_G
level of the noise that is assigned to the critical band that describes the masking characteristic of the noise for one or more tones of the noise in the critical band

3.22
amplitude modulation
regular fluctuation in the level of sound, the period of fluctuations being related to the rotational speed of the wind turbine

Note 1 to entry: This characteristic might be described by a listener as a repetitive 'swish', 'whoomph' or 'thump'.

3.23
impulsivity
sudden onset of a sound

Note 1 to entry: The character and prominence of the impulse at the immission point depends on the character of the emitted sound, the distance and propagation path from the sound source and the background sound. Therefore the impulsiveness of a sound is characterised by the onset of the sound independently of the category of the sound source.

Note 2 to entry: The definition includes only the onset of a sound, not the sound as a whole. "Sudden" is based on an auditive judgement, which is expressed in terms of physical measurements in this method.

3.24
test plan
document that identifies the goals and objectives of an investigation or measurement campaign to make it possible to select the appropriate setup

3.25
long term measurements
series of continuous unattended measurements typically for several days, weeks, or months

3.26
short term measurements
series of attended measurements

3.27
receptor position
position where the sound characteristics are to be determined

3.28
remote sensing device
RSD
light detection and ranging (LiDAR) using light or sonic detection and ranging (SoDAR) using acoustical signals to determine the wind speed or wind speed profile

3.29
binning wind speed
wind speed usually at 10 m height used for binning measurement results

Note 1 to entry: The binning wind speed can be measured or calculated.

3.30
mode of operation
operational mode of a wind turbine characterized by the sound and power curve for a certain power and sound power output

3.31
reference roughness length
z_{0ref}
roughness length of 0,05 m used for converting wind speed between heights by using a logarithmic wind speed profile

3.32
sound relevant wind turbines, pl.
group of wind turbines with most relevant contribution to the sound characteristic at receptor position used for the determination of wind speed

3.33
wind shear
change in wind speed with height

3.34
nacelle anemometer
anemometer mounted on the nacelle of the wind turbine

3.35
averaging time /measurement interval
length of time for a measurement interval of typically 10 s, 60 s or 600 s

Note 1 to entry: Averaging can consist of applying shorter intervals, for example 1 s to 10 s logging data building up to the required interval.

3.36
SCADA data
data achieved from the wind farm data system

Note 1 to entry: Typically included in SCADA data are power, RPM, wind speed, yaw position pitch. Sometimes air temperature, barometric pressure, relative humidity etc. ,are included as well.

3.37
blade passage frequency
number of times a blade passes a given point on the rotor disc in 1 s

3.38
far-field location
location which is at a distance from the wind farm corresponding to the receptor location

4 Symbols and units

D	rotor diameter (horizontal axis wind turbine) or equatorial diameter (vertical axis wind turbine)	(m)
H	height of rotor centre (horizontal axis wind turbine) or height of rotor equatorial plane (vertical axis wind turbine) above local ground near the wind turbine	(m)
L_{A} or L_{C}	A-weighted or C-weighted sound pressure level	(dB)
L_{Aeq}	equivalent continuous A-weighted sound pressure level	(dB)
$L_{WA,k}$	apparent sound power level, where k is a wind speed bin centre value	(dB)
log	logarithm to base 10	
P_{m}	measured electric power	(W)
T_{C}	air temperature	(°C)
T_{K}	absolute air temperature	(K)
U_{A}	type A uncertainty	(-)
U_{B}	type B uncertainty	(-)
V_H	wind speed at hub height, H	(m/s)
V_{bin}	binning wind speed at 10 m height	(m/s)

V_P	derived wind speed from power curve	(m/s)
V_z	wind speed at height, z	(m/s)
V_{nac}	wind speed from nacelle anemometer	(m/s)
f_T	frequency of the tone	(Hz)
f_c	centre frequency of critical band	(Hz)
p	atmospheric pressure	(kPa)
z_0	roughness length	(m)
z_{0ref}	reference roughness length, 0,05 m	(m)
z	anemometer height	(m)
κ	ratio of normalised wind speed and measured wind speed	(-)
S	power spectrum	(-)
L_{pk}	magnitude of fundamental peak	(dB)
L_m	masking level	(dB)
p_{am}	prominence ratio for amplitude modulation	(-)
P_I	prominence of impulsivity	(-)
BPF	blade passage frequency	(Hz)

5 Outline of method

This part of IEC 61400 defines a range of procedures to be used in the measurement, analysis and reporting of acoustic characteristics of a wind farm or a wind turbine at the receptor position. The intention of the document is to provide a range of methods and tools to apply to describe different acoustical characteristics of wind turbine noise. Not all methods in this document are required in all investigations, and where multiple options are available, choose a single option. Instrumentation and calibration requirements are specified to ensure accuracy and consistency (repeatability) of acoustic and non-acoustic measurements. Acoustic measurements characterise the sound while non-acoustic measurements characterise the operational and atmospheric conditions during which the acoustic data were collected. Wind speed and wind direction are essential in this. All parameters to be measured and reported are identified, as are the data reduction methods required for obtaining these parameters.

Application of the methods described in this document provide one or more of the parameters, the A-weighted sound pressure levels, spectra, tonal audibility, impulsivity and amplitude modulation at a receptor location relevant for the investigation under varying wind speeds or wind directions. The wind speed range is related to local or national requirements, the purpose of the investigation, and is identified in the test plan. The method is not restricted by operational (hub height) wind speed but strong winds at the microphone location can complicate the data evaluation as described herein.

Measurements of acoustical characteristics, meteorological conditions and wind turbine performance are made simultaneously.

The informative annexes included cover:

- rating levels (Annex A)
- infrasound (Annex B)
- low frequency sound evaluation (Annex C)
- examples for a test plan (Annex D)
- objective method for assessing the audibility of tones in noise – survey method (Annex E)

- data exclusion tools (Annex F)
- AM adaptions (Annex G)
- additional analysis tools (Annex H)
- secondary wind screens, façade mounted microphones and proxy locations (Annex I)
- sound emergence (Annex J)
- meteorological effects (Annex K)
- ISO PAS 20065, Implementation – Area of further consideration (Annex L)

6 Instrumentation

6.1 Acoustic instruments

6.1.1 General

The following equipment is necessary to perform the acoustic measurements as set out in this document.

6.1.2 Equipment for the determination of the equivalent continuous A-weighted sound pressure level

The equipment shall meet the requirements relevant to this document of an IEC 61672 series class 1 sound level meter.

The diameter of the microphone diaphragm shall be no greater than 13 mm and shall be used within its specified environmental conditions.

6.1.3 Equipment for the determination of A-weighted or Z-weighted 1/3-octave band spectra

In addition to the requirements given for class 1 sound level meters, the equipment shall have a constant frequency response over at least the frequency range given by the 1/3-octave bands with centre frequencies from 10 Hz to 10 kHz. The filters shall meet the requirements, relevant for this document, of IEC 61260 for class 1 filters. The equivalent A-weighted or Z-weighted continuous sound pressure levels in 1/3-octave bands with centre frequencies from 10 Hz to 10 kHz shall be determined simultaneously.

The diameter of the microphone diaphragm shall be no greater than 13 mm and shall be used within its specified environmental conditions.

6.1.4 Equipment for the determination of narrow band spectra

The equipment shall fulfil the relevant requirements for IEC 61672 series class 1 instrumentation in the 8,9 Hz to 11 200 Hz frequency range.

The diameter of the microphone diaphragm shall be no greater than 13 mm and shall be used within its specified environmental conditions.

6.1.5 Acoustical calibrator

The calibrator shall fulfil the requirements of IEC 60942 class 1 and shall be used within its specified environmental conditions.

6.1.6 Audio recording and playback systems

A data recording and playback system is a recommended part of the measurement instrumentation. If used for analysis (other than re-listening), the entire chain of measurement instruments shall fulfil the relevant requirements of the IEC 61672 series, for class 1 instrumentation.

6.2 Non-acoustic instruments

6.2.1 General

The following equipment is necessary to perform the non-acoustic measurements set forth in this document.

6.2.2 Wind speed measurement systems

The wind speed can be measured with a mast mounted anemometer. The anemometer should be, as a minimum, a class B instrument in accordance with IEC 61400-12-1 with an operational uncertainty of ±0,5 m/s at 10 m/s. It shall be capable of measuring the average wind speed over time intervals synchronized with the acoustic measurements.

SoDAR, LiDAR or other wind speed measurement systems can also be used for determination of wind speed. Documentation of their accuracy and reliability shall be available, and the accuracy of the measurement system shall be stated.

6.2.3 Other instrumentation (temperature, humidity, rain, pressure, distance, temperature gradient, satellite positioning system)

For distance measurements (for instance using a laser range finder) the accuracy shall be better than ±2 %. For a satellite positioning system (GPS or other), the accuracy shall be at least to within 10 m.

A rain gauge is required for unattended measurements. Precipitation should be determined with an accuracy of 5 % and a minimum resolution of 0,5 mm/h is recommended.

Depending on the purposes of the measurements, temperature, humidity and atmospheric pressure can be required. If these parameters are measured, their accuracy shall be documented. Typically, temperature shall be measured with an accuracy of ±1 °C. The atmospheric pressure shall be measured with an accuracy of ±1 kPa. The relative humidity shall be determined with an accuracy of 5 %.

Other parameters can be optionally measured depending on the need for the campaign such as cloud cover, temperature profile, or wind velocity profile. In each case the accuracy of the measurements shall be reported, and documentation shall be available to determine the accuracy and reliability of the measured parameter.

6.3 Traceable calibration

The following equipment shall be checked regularly and calibrated by an accredited laboratory with traceability to national or primary standards. The maximum time from the last calibration shall be as stated for each item of equipment:

1) acoustic calibrator (12 months);
2) microphone (24 months);
3) integrating sound level meter (24 months);
4) spectrum analyser (24 months);
5) audio recording and playback system (24 months), if used for analysis.

The following equipment should at least be verified at regular intervals to ensure proper operation:

a) anemometer (24 months); for ultrasonic anemometers (72 months);

b) electric power transducer (24 months);

c) temperature transducer (24 months);

d) atmospheric pressure transducer (24 months);

e) instrumentation to measure distance (24 months).

Where temperature and atmospheric pressure measurements are made only to give general information about the meteorological conditions during the measurement, an internal verification of the instrument is sufficient.

6.4 Acoustic field calibration

The complete measurement chain shall be field calibrated at least at one frequency before and after the measurements, or, if the microphones are disconnected and reconnected during the measurements, using an acoustic calibrator.

Measurement equipment shall be recalibrated at regular intervals during measurements to verify validity of the calibration. These regular intervals are dependent on weather conditions that occur during the measurements. All calibrations should be reported, along with any drift. A calibration drift of less than 0,5 dB is considered appropriate where a measurement has taken place over multiple days. A calibration drift greater than 0,5 dB but less than 1,0 dB need not disqualify the measured data, provided that subsequent calibration to the manufacturer's specification confirms that there is no defect in the system, and that the recorded time history does not exhibit any anomalies that might indicate more significant deviations in system sensitivity during the survey. Where the system exhibits a calibration shift greater than or equal to 1,0 dB, those measurements should be discarded. Furthermore, the error in the entire measurement system should be found and documented and equipment causing the drift should be replaced.

Guidance on calibration of noise monitoring systems can be found in ISO 20906:2009/AMD1:2013, 4.8.

6.5 Time synchronization

Synchronization of the acoustic data with relevant wind turbine data and other non-acoustic instrumentation shall be carried out as far as practicable. The overall time reference should be local time.

The synchronization between acoustic, non-acoustic, and wind turbine SCADA data shall be maintained during all the measurement time with maximum offset below 10 % of the averaging time including any long-term drift. This can be done by comparing the time offsets at the beginning and end of the measurement campaign with a reference clock such as a satellite-based radio navigation system.

The internal clock of different relevant wind turbines will probably not be synchronous for different reasons. They can be part of different groups or owned by different operators. Time synchronization has been known to drift over long periods. It would be prudent to verify time synchronization at regular intervals during the campaign. If applicable, daylight saving time adjustments should be accounted for across all data sources. All possible gaps shall be noted and corrected by post processing.[1]

[1] The timestamp can indicate the end or the beginning of the measurement period for the different instruments or data sources. Therefore care should be taken when correlating these data from differing sources.

7 Test planning

7.1 General

As an initial step in a campaign to measure wind turbine or wind farm sound at a far-field location, it is mandatory to determine the required scope of the campaign, and to set up a test plan, to clarify how measurement data are to be collected and analysed.

The test plan shall include considerations of the planned measurement campaign including sound characteristics and non-acoustic measurements that need to be measured in order to describe the sound from the wind farm.

Logs from residents, operators or other stakeholders can provide information in forming a test plan.

7.2 Planning acoustic measurements

7.2.1 Sound characteristics

The sound characteristics addressed in this document include:

1) sound pressure level (L_A) (see Clause 11);
2) tonal audibility (see Clause 12);
3) amplitude modulation (see Clause 13);
4) impulsivity (see Clause 14);
5) low frequency sound evaluation (see Annex C).

If more than one characteristic of sound immission is being investigated (for instance sound pressure level and tonal audibility), it can be necessary to combine types of measurements, for example measurement durations (long- and short-term measurements) and measurement locations (measurement directly at receptor locations and measurement at proxy locations) or other ambient conditions of testing.

7.2.2 Sound sources to be considered

The measured total sound is the sound of the wind farm under investigation, plus potential other industrial sound sources (e.g. other wind farms), other environmental sound sources, traffic noise, wind induced sound (wind speed dependent), natural sound sources (animals, insects etc.) and other background sound sources at the receptor location. Therefore, it is important to consider how background sound levels can influence the measurement.

It is typically required to measure the sound as close as possible to the relevant receptor location, and to measure under typical situations where these other sound sources exhibit a representative level and characteristics. Microphones shall be set up in a way to measure all considered sound sources directly.

It is desirable that any potential masking background sound is avoided as much as possible during the measurements. That can mean:

- avoiding measurement periods where disturbing background sounds occur or discarding data points that are obviously contaminated by background sound;
- to choose a measurement location so that background sound sources have the least influence on the measurement data, for example by increasing distance to vegetation to avoid wind induced noise, or to have blocking objects between background sound source and microphone (e.g., a wall or building in between the microphone and a road or other distinct background sound source). Façade noise measurements should be considered as described in Annex I. Care should be taken to avoid positioning the microphone in the vicinity of a densely forested or vegetated area, where possible, so as to reduce wind

induced vegetation sound. In an agricultural area, consideration should also be given to the crops being planted, their timing, and the potential for vegetation sound or bird scarers at different times of the growing season.

Background sound sources that cannot be avoided can be accounted for by background sound correction. Background sound correction can be carried out in different ways depending on the characteristics of the background sound and the purpose of the measurement:

– In the case where background sound depends on wind speed or wind direction (typical wind induced noise in vegetation), the correction should be done by using bin analysis of total sound and background sound with respect to wind speed or wind direction, in order to perform background sound correction within the respective bin. It can be necessary to distinguish periods with strong or weak wind shear, for example night and day.
– In the case where background sound is related to time and not to wind speed (typical traffic noise, industrial noise), the correction can be done by comparing comparable time periods of measurements with the wind farm operating or shut down.

In situations where background sound is so high that it is masking the wind turbine sound, and the wind turbine sound cannot be determined, the measurement result can only confirm the upper limits of the wind turbine sound.

An alternative approach is to make measurements closer to the source where the signal-to-noise ratio is large enough and to extrapolate the wind turbine sound contribution at the receptor position by predictions. Predictions based on in-situ sound power measurements in accordance with IEC 61400-11 are another alternative. Note that these methods are not normally appropriate for the assessment of sound characteristics (such as amplitude modulation or tonal audibility) as the perception is very dependent on the local sound environment.

Where background or sound sources other than the wind turbine sound under investigation need to be explicitly determined and quantified, it is necessary to define the source of these sounds, their characteristics, and from which parameters the level and characteristic of these other sound source can depend, for example, wind speed, time of day (week, or year), weather, etc. Measurement conditions, setup and data analysis can have to be chosen according to such dependencies. See 11.6.2 for more information.

7.3 Determination of representative conditions

The times of interest can depend on the overall goal of the measurement campaign. Some common criteria for data validity include a combination of the following:

1) Wind turbine operational wind speed range

   The hub height wind speed could be used as a way of isolating specific weather conditions that would not otherwise be able to be isolated, for example, if measurements are for stall-controlled wind turbines where the maximum sound power occurs at a very high hub height wind speed. Test plan requirements can indicate if the wind speed ranges of interest are wind speed bins from cut-in to cut-out, or alternatively a single bin that covers wind speeds resulting in maximum acoustic output.

2) Electrical power range

   This condition could be a range of electrical power of the relevant wind turbines that would be of interest in assessing wind turbine sound at the receptor location. The electrical power range, for example, could isolate wind turbine operational conditions where the sound output is expected to be maximum.

3) Specific wind direction conditions

   This condition can be true when the wind is blowing from the relevant wind turbines in the direction of interest (for example downwind, crosswind, prevailing direction or all wind directions). For this condition consideration needs to be given to the correlation between wind direction across the relevant wind turbines, and between the relevant wind turbines and the measurement location. It is suggested that wind angles be defined in a range (for example ±45°).

4) Wind speed measured at low heights, between 2 m and 10 m height close to the receptor location

   This quantity can be used to isolate only conditions where background sound contamination is minimised.

5) Time of day

   Depending on the purpose of the measurements the data can be limited to daytime and evening or night time periods in order to reduce the potential for contamination, or to evaluate specific patterns of sound output if necessary for the purpose of the measurement. The best signal-to-noise ratio is typically during night time conditions usually starting after persons in the locality are likely to have ceased outdoor activities and 30 min before dawn chorus (morning bird sounds), or the time at which local human outdoor activities are likely to start for the day. The use of information on atmospheric stability could be helpful in determining the appropriate time frame of measurements.

6) Meteorology

   The meteorology might affect the sound propagation and thereby the results of the measurements in the far-field location. Examples of parameters that will affect the measurements can be: temperature and humidity which affect the atmospheric absorption (see ISO 9613-1), temperature gradient which can vary between day and night time, atmospheric stability, turbulence, shear and veer will affect the propagation. For that reason, it is important to consider which conditions are representative conditions of interest and to plan the campaign accordingly. It might be relevant to measure several metrological parameters to filter for non-relevant conditions or bin data and thereby reduce variability and uncertainty in the measurement bins.

7) Verification of wind turbine operation

   Confirming times where wind turbines are actually operating as expected (for example not during ramp up or ramp down, in the right mode of operation, etc.)

8) Weather conditions

   Rainfall conditions can have a dramatic effect on the sound levels in the far-field locations. Consideration should be made to identify whether these periods should be included or excluded from the valid measurement times.

Other criteria can be appropriate for use based on the purpose of the measurements. The test plan should outline the required filters and their intended purpose.

7.4 Effects of site conditions on measurements

The test plan should describe and assess suitable site conditions for the purpose of the measurements and how these conditions affect the measurement. Examples of conditions that potentially can affect the measurements:

- animal sounds (e.g. insects, frogs, birds etc.);
- acoustical ground conditions such as hard versus soft ground, roughness length etc.;
- season (with or without leaves on trees, streams running, etc.);
- vegetation (crops, deciduous plants etc.);
- traffic or other sound sources (industrial noise, farming activity, other wind farms);
- weather (wind direction, rainwater course after rain (faster stream or river flows), snow, ice etc.);
- daily variations;
- sound propagation conditions (e.g. atmospheric stability, wind shear, temperature gradient, humidity, cloud cover, etc.).

7.5 Acoustic measurements

The test plan should describe and assess suitable acoustical parameters for the purpose of the measurements. Acoustical parameters could be:

1) sound pressure levels;
2) percentiles, for example L_{A90}, L_{A50};
3) 1/3-octave bands;
4) narrowband spectra.

Audio recordings shall be carried out uncompressed or using lossless signal compression. Where data compression format or similar format recordings are carried out, such recordings shall be strictly limited to ancillary purposes such as identifying a certain sound source or event.

8 Setup of acoustic measurements

8.1 Measurement locations

8.1.1 General

Where the purpose of the measurements is to establish the overall sound pressure level at or near a wind farm neighbour's dwelling (for the purposes of compliance with noise limits), the position of the microphone should be away from any large reflective surface other than the ground. This is ideally accomplished with a separation distance of 5 times the wavelength of the lowest frequency of interest, typically 15 m to 20 m from any such surfaces.

The locations should be chosen with consideration for local sources of noise contamination such as sight-lines with regard to traffic noise sources, local noisy equipment related to the dwelling such as externally mounted (or vented) air conditioning or heating equipment. The measurement locations shall be representative of the receptor location being evaluated (such as a dwelling location). The receptor position can be representative for a larger group of dwellings with similar conditions.

8.1.2 Proxy location

If a location is chosen that is different in distance or acoustic environment, or both, from the location being evaluated, the location is considered a proxy location. Proxy locations should be selected to be representative of the sound propagating from the source to the receptor location and such that they are most impacted by the same wind turbine in the farm as the receptor location. Some examples of microphone proxy location choices are provided in Annex I. Proxy locations are of limited applicability for determining characteristics like tonality, amplitude modulation or impulsivity.

NOTE The following is proposed: The representative receptor position will have the same background sources and similar distances to the sound relevant wind turbines. A difference of less than 1,0 dB from predicted overall SPL of sound relevant wind turbines is considered acceptable over the more exposed dwelling. For showing compliance at a different location at the group of houses, the predicted difference will be corrected. For larger differences, other proxy locations will be considered (Clause I.4).

8.1.3 Mounting

The preferred method for microphone mounting is a free-field microphone that is protected by a two-stage or oversize wind screen in order to obtain an appropriate signal-to-noise ratio with respect to wind-induced noise. Such a microphone could be mounted on a tripod or pole. Care should be taken to ensure that parts of the mounting system do not exhibit or produce noise in the presence of wind. This can sometimes occur where the mounting poles contain holes for bolts or fasteners that are left open, or protrusions such as bird spikes.

If a higher signal-to-noise ratio is desirable, in some situations it can be possible to mount the microphone directly onto a vertical surface of the dwelling. The façade shall be plane within a tolerance of ±0,05 m, within 1 m distance from the microphone, and the distance from the microphone to the surface edges of the façade shall be more than 1 m. For more details on façade mounted microphones see Annex I and ISO 1996-2:2017, Annex B.

For a façade mounted microphone, the relevant wind turbines at the measurement location should be within 45° of the normal to the façade. The applicability of these alternative mounting methods depends heavily on-site conditions, and thus, justification of the use of such methods and their effects on the resulting sound levels shall be reported.

Façade mounted microphones cannot be used for assessing tonal audibility, amplitude modulation or impulsivity.

9 Non-acoustic measurements

9.1 General comments

Wind turbine operation depends on wind conditions and the sound emission is therefore dependent on the wind speed at the wind turbine(s). The background sound is usually dependent on the wind speed near the receptor location. To determine the sound behaviour of a wind farm it is necessary to know the corresponding wind speeds for the recorded sound data.

There are several methods of determining wind speed. The determination of wind speed should be carefully selected on the basis of the aim of the measurement described in Clause 7 (test planning).

Different methods for different receptor location (receivers) on the same wind farm can be necessary.

9.2 Data sampling

Wind speed, electrical power and other operational parameters should be sampled at a rate of at least 1 Hz. Nacelle wind speed and electrical power output can be provided by the wind turbine operator.

An averaging period between 10 s and 10 min should be used.

9.3 Wind speed

9.3.1 General

In the context of wind turbine sound measurements, the wind conditions play a critical role. The wind conditions at various positions can influence the measured sound levels in the far-field locations. Subclause 9.3 outlines the different considerations and requirements for wind speed measurements and analysis.

The wind speed at various heights can be used to obtain important information about conditions of the sound measurement. Generally, the sound emitted by the wind turbines is correlated to the wind speed at the wind turbine hub. Wind induced noise from vegetation is correlated to the physical qualities of the vegetation such as the height of the vegetation. Wind speeds near the ground would correlate with vegetation sound from low bushes, shrubs and trees; wind speeds between 2 m and 10 m height could correlate to vegetation sound from trees in the immediate vicinity of the microphone (depending on their height), and wind at higher elevations could be correlated to vegetation sound if the topography of the site exposes trees to different wind conditions compared to the microphone location. Finally, the wind speed at the microphone height would correlate most with wind-induced self-noise from the measurement system. The test plan should make considerations for the necessity to quantify these separate sounds in order to ensure sufficient data quality.

Wind speeds can be either measured or derived. Measured wind speeds are measured directly at the desired height, whereas derived wind speeds are calculated from other quantities such as the electrical power output of wind turbine or calculated from the wind speed measured at a different height using IEC 61400-11:2012, Equation (D.1).

Wind speeds can be used for two primary purposes, either binning the data according to set parameters to allow the acoustic values to be averaged within the bins or filtering the data to exclude data which does not meet the required conditions (often to minimise background sound contributions). Generally, only a single wind speed data source should be used to bin data, whilst multiple wind speed data sources can be used to filter data if desired.

For example, in an attempt to assess the sound pressure levels during maximum sound power level conditions, data could be binned according to the hub height wind speed of the wind turbine and the microphone height wind speed would then be used to filter out intervals where the self-noise would be problematic. This example is summarised in Table 1.

Table 1 – Example 1: Wind speed data categorization – Maximum sound power level emissions

Quantity	Measured /Derived	Binning or filtering	Range of interest
Hub height wind speed	Derived	Binning	7 m/s to13 m/s
10 m height wind speed	Measured	Filtering	< 5 m/s
2 m height wind speed	Measured	Filtering	< 4 m/s

Conversely, Table 2 shows an example where 10 m height wind speed could be used as the binning wind speed, and the hub height wind speed could be used as a filter to remove times when the wind turbine would not be generating the desired electrical output or acoustic sound power.

Table 2 – Example 2: Wind speed data categorization – Maximum sound power level emissions

Quantity	Measured /Derived	Binning or Filtering	Range of interest
Hub height wind speed	Derived	Filtering	> 7 m/s
10 m height wind speed	Measured	Binning	0 m/s to 5 m/s

In both of these examples the maximum sound power level of the wind turbine is emitted for hub height wind speeds above 7 m/s. The aim is to assess for this condition by either minimising, or correcting for, the background sound contribution (see 11.1 for details of this sound pressure level analysis).

Other examples could include only a single wind speed reference being used, for example binning between 0 m/s to 12 m/s derived hub height wind speed.

When converting wind speeds (measured or derived) between different heights the possible effect of wind shear has to be considered. This is particularly relevant when assuming a measured wind speed at a height significantly lower than the turbine hub height can adequately correlate with turbine sound emission variation with wind speed at the rotor.

If measurement devices are located in the vicinity of wind turbines or significant terrain features, they could be disturbed by the wake of wind turbines or terrain effects. When wind speed and wind direction measurements are disturbed by wind turbine wake or terrain effects, they should not be relied upon to be accurate. For any of these devices which are not close to the receptor location longer averaging periods should be used. The nacelle wind direction should be used with caution as there is always a concern for accuracy.

9.3.2 Binning wind speed related to wind farm operation, V_{bin}

9.3.2.1 General

The preferred method of determining the binning wind speed for overall sound is based on the power output based on the power curve and the nacelle anemometer as described in IEC 61400-11:2012 and IEC 61400-11:2012/AMD1:2018, 8.2.1. This value is recalculated to 10 m height in accordance with IEC 61400-11:2012, Equation (29). The wind speed reference shall be called V_{bin}.

9.3.2.2 Wind speed for single wind turbine of interest

If only one wind turbine is of interest the same method as described in IEC 61400-11:2012 and IEC 61400-11:2012/AMD1:2018, 8.2.1, shall be directly used.

9.3.2.3 Wind speed for multiple wind turbines of interest

For the case where the operation of multiple wind turbines is of interest, the wind speed shall be determined for every wind turbine with the same method as described in IEC 61400-11:2012 and IEC 61400-11:2012/AMD1:2018, 8.2.1. The determination of the binning wind speed depends on the number of wind turbines, the layout of the wind farm and the position of the receiver.

For smaller wind farms (typically up to 5 wind turbines) and comparable sound contributions from all wind turbines to the receptor location the mean wind speed from all wind turbines should be used as reference wind speed.

For larger wind farms or when the sound contribution of the wind turbines on the receptor location is very different, only some of the wind turbines should be chosen for the determination of the binning wind speed. For an objective method to determine which wind turbines have an influence on the overall sound level at the receptor location, the wind turbines have to be sorted by the predicted sound contribution at the receptor location. The quietest wind turbine will be excluded from the prediction and it will be checked if the total wind farm sound level without the quietest wind turbine has reduced by more than 1,0 dB. If not, the next quietest wind turbine has to be excluded from the prediction. That will be done as long as the predicted sound change for each step is less than 1,0 dB lower than the sound of all wind turbines. The remaining wind turbines are considered as the sound relevant wind turbines. The mean wind speed from the sound relevant wind turbines has to be used for the determination of the binning wind speed. Typically this will result in the most dominant 2 or 3 wind turbines determining the binning wind speed for a given measurement location. The mean wind speed shall be determined by arithmetically averaging the wind speeds derived from each individual wind turbine.

Further options for determining the binning wind speed by wind farm operation are measurements at heights comparable to the turbine rotors, made with anemometers mounted to meteorological masts or with a remote sensing device (RSD). If measurements at different heights are available, the wind shear could be determined to allow for the estimation of wind speeds at heights higher, or lower, than those measured. To carry out this shear corrected wind speed estimation, it is usually necessary to have a measurement height within ±40 % of the turbine hub height, and a second measurement height at least 15 m vertically distant from the first measurement height. Measurements at multiple heights can also be used to investigate shear effects at certain receivers.

If measurement devices are located in the vicinity of wind turbines, they could be disturbed by the wake of wind turbines. The values during wind directions when these measurement devices are disturbed by wind turbine wake are to be excluded from the data evaluation. Similarly terrain effects (shielding or funnelling) should be considered where these might affect measurements in some wind directions. This is most easily assessed by comparing two wind speed sources in terms of wind speed and wind direction.

9.3.2.4 Wind speed with the wind turbines parked

Generally, when assessing background sound, the same method shall be applied as for the measurements of the wind farm operation. However, there are limitations to some methods, namely power curve derived wind speed and nacelle anemometer wind speed. The power curve method cannot be applied during wind turbines parked.

Ideally, a (permanent) meteorological mast in a suitable position or remote sensing devices are available with hub height or near hub height wind speed measurements. These wind speed measurements should be correlated with the wind speed determined from the power data during wind farm operation and subsequently corrected with the derived factor for use in wind turbine parked period as per IEC 61400-11. The derived factor can be wind direction dependent, and it can be necessary to determine the factor for different sectors.

If using the nacelle anemometer as alternative wind speed measurement, it should be noted that there are several reasons for the inaccuracy of this wind speed data. Data from where the turbine is off might not be directly comparable to wind data measured during operation. Blades can obstruct the wind flow in a parked position and even when idling, large slow-moving blades can reduce the inflow to the anemometer on the nacelle.

If several different wind speed measurement devices are available, it is strongly advised to compare all available data and chose the most appropriate method for the assessment.

NOTE 1 When using the nacelle anemometer for wind speed determination, wind data will be compared immediately before and after the time period where the shut down occurs to estimate the influence of the blade on the nacelle anemometer reading. If there is an unexpected drop or increase in wind speed when the wind turbine has been stopped, the data might not be reliable. Furthermore, a comparison of the wind speed vs. sound pressure level plots with wind farm on and off will be appropriate. If the plotted data looks sensible, the nacelle wind speed data can be used.

NOTE 2 The wind speed measurement measured by a meteorological mast or remote sensing device can also be influenced by the operation of other turbines. Where possible, and where the device is installed for the purpose of the sound measurement, it will be placed in a representative location where the wind speed measurement is the least influenced by the wake of wind turbines. If the permanent meteorological mast is affected by wake from wind turbines, those periods during wind turbine operation will be removed as per 9.3.2.3. All periods during which the wind turbines are parked can be used.

9.3.3 Binning wind speed related to background sound

If wind induced background sound is a particular and significant part of the investigation (e.g. where background sound correction has to be done or where potential masking by wind induced background sound has to be considered), the wind speed for background sound can be used as the binning wind speed, and other wind speeds would have to be used to filter for the appropriate operation of the wind turbines.

When choosing the background sound wind speed as the binning wind speed, the relevant height should be informed by considering, where most of the wind induced background sound is being emitted to the measurement location. Usually, this is from vegetation like trees, bushes or crops or other obstacles and objects in the nearby vicinity of the measurement location. Thus, an anemometer shall be placed close to these objects creating the wind induced sound, in a representative height of the respective sound sources (typically between 2 m and 10 m). Care shall be taken, that the anemometer and related mast installations do not add further wind induced noise to the microphone location.

In some cases, wind induced noise can also stem from objects further away from the microphone location, such as objects on a topographically exposed location like a mountain ridge (under otherwise wind sheltered conditions near the microphone) or larger areas of forest. In such cases, wind speed determination at larger distances and near to the aforementioned objects is recommended. Wind speed measurements within the wind farm, potentially the very same wind speed as is used for the determination of the wind farm sound, may be used as a proxy for the aforementioned larger-distance wind speed measurements (see note in 9.4 on the relation between distance from wind measurement to object and limitations of short averaging times).

In case of several objects of wind induced sound immissions to a microphone location, a good compromise has to be found in order to characterise the wind speed at the object of sound creation which contributes most to the background sound levels under consideration.

The distance between the wind speed sensor and the object of (wind induced) sound emission has influence on the correlation between the wind speed measured and the wind speed hitting the object. For large distances (100 m and more), the correlation will generally be low (wind travel time might be considered to increase correlation to a certain limited extent), consequently, short averaging times (like 10 s) do not make a lot of sense and will mostly not lead to meaningful results.

Remote sensing devices (RSDs) might not be appropriate for measuring the local wind speeds at low heights near the measurement position.

9.4 Wind direction

In addition to wind speed, the sound from wind turbines is dependent on the orientation to the receiver and the wind direction. In downwind direction the highest A-weighted sound pressure levels are expected, although other sound characteristic can vary with direction. The background sound at receiver positions is wind direction dependent as well, although sometimes to a lesser extent, depending on the distances of the dominant background sound sources to the microphone position.

In a similar manner as wind speed, the wind direction information from various locations could either be used for binning the data or for filtering the data. In all cases, there should only be one source of wind direction for binning and all other sources could be used for filtering the data.

NOTE For example, wind direction derived from wind turbine SCADA data could be used to bin the data according to propagation conditions, and wind direction near the microphone could be used to filter out parts of that data where the wind is blowing from nearby vegetation in order to reduce the contamination if possible.

There are several methods of determining wind direction. The determination of wind direction should be carefully selected on the basis of the aim of the measurement.

Wind direction data shall be sampled with a rate of at least 1 Hz. Nacelle wind direction can be provided by the wind turbine manufacturer or operator. Wind turbine yaw can also be used. However, the yaw angle is only reliable for determining changes in nacelle direction, but less reliable for absolute angle, unless this is verified prior to, or during, the measurements.

Where wind direction is required to be averaged, this should be done using vector averaging owing to the discontinuity at north.

Options for determining the wind direction are measurements with wind vanes or directional anemometers (such as ultra-sonic sensors), RSDs and with nacelle instrumentation. As for measuring wind speed it is not possible to reliably estimate wind directions at significantly different locations (either vertically or horizontally) due to the large impact of terrain effects and differing airstream profiles with height. Therefore, use of wind direction measured at heights significantly different to those of the rotor are generally poor at correlating with wind direction variation at the sound emission location.

9.5 Precipitation

Precipitation should be measured at positions representative of rainfall at the receptor position(s). The rainfall data will be used to minimise the contribution of rain and water course sound to the measurements. Rain gauges should be accurate enough to determine whether rainfall is occurring or not in each measurement interval (see 6.2.3). Where multiple receptor locations are being monitored concurrently, precipitation measurements should be made sufficiently close to the receptors to appropriately determine the likelihood of rainfall or not within the measurement resolution time frame being used. For a 1 min time frame, the rain gauge necessitates being closer to the receptor to be representative than with a 10 min time frame.

9.6 Temperature, humidity, etc

Air temperature, relative humidity and air pressure (optional) have an influence on the air absorption. These parameters should be measured during the measurements, preferably at a height of 1 m to 1,5 m above ground. The measurement position should be between the wind farm and the receptor location.

For more detailed information on the influence of meteorology on sound propagation see Annex K.

9.7 Wind turbine parameters (optional if necessary for assessment)

The following parameters can be used for describing the operation of the wind turbines or wind farm:

- operational modes of wind turbines (power curve for wind speed determination);
- status of wind turbines (off for whatever reason – non-normal situation);
- “automated” grid restriction which results in power curtailment if triggered by grid company;
- RPM and power are used to determine on/off status for background sound measurement or to confirm the status;
- rotor RPM is also a key input to AM analysis (although this can be done without wind turbine RPM data if necessary), and can be very useful for investigation of tonal audibility also.

10 Data reduction

10.1 Bin analysis

The basic principle is that all acoustic parameters are binned and averaged with respect to wind speed and wind direction. Wind speed bin width is usually 1 m/s referenced to the binning wind speed. Wider bins can be used if relevant. This could also be a single bin including all data (with or without filtering). Binning can be made according to more parameters at the same time.

Wind direction is binned either in equal sectors relating to north, or sectors relating to the orientation between the wind turbines and the receptors. When binning relating to north this is usually done in 30° wide sectors. When binning relating to the orientation between the wind turbine and the receptor, wider sectors relating to downwind, crosswind or upwind are usually used.

The downwind sector is often considered to be the vector between the wind turbines and the receptor position ±45°.

Some parameters like tonal audibility and amplitude modulation might not be present at all times. For such parameters the percentage of presence is determined in bin analysis as well.

10.2 Data recommendations

The accuracy, uncertainty or reliability of a measurement is to some extent dependent on the amount of data acquired. With a large amount of data, tendencies become clearer and the scatter is likely to be reduced. When data are sorted into wind speed bins (wind speed and direction) the data are expected to be representative for a specific condition. Filtering or binning after more parameters (high power, day or night etc.) can decrease the scatter even further and make the results more descriptive for a given situation. It is not straightforward to set up requirements on the necessary amount of data but it is necessary to have sufficient data to make a reliable statistical treatment. The standard deviation on the mean value can be used as a good indicator of the quality and robustness of the results.

Note that when analysing the measurements in the laboratory it sometimes happens that more data has to be discarded than expected due to disturbances.

10.3 Uncertainty

10.3.1 General

The uncertainty on the measurement result, whether it is the sound level or the tonal audibility, is an important information on the accuracy and the validity of the result. Decisions on compliance can be made from an understanding that the results are not decisive values on their own. In many situations the principle that noncompliance is only demonstrated if the uncertainty is taken into account is the governing principle. Large uncertainties can sometimes lead to non-conclusive situations.

An estimate of the uncertainty can be calculated from average and standard deviation within a bin.

The uncertainty of the result of a measurement can be based on the standard deviation described in 10.3.2 to 10.3.4.

10.3.2 Calculation of average sound pressure level and uncertainty per bin based on measurements

The average sound pressure level, $\bar{L}_{\mathrm{k}}$, for is calculated by Equation (1):

NOTE Equation (1) applies when sound pressure levels are determined as equivalent A-weighted sound pressure levels. For statistical levels like L50, l90 or L95 arithmetic averaging as described in Equation (8) applies.

$$\bar{L}_{\mathrm{k}} = 10 \cdot \log\left(\frac{1}{N}\sum_{j=1}^{N} 10^{\left(\frac{L_{\mathrm{j,k}}}{10}\right)}\right) \tag{1}$$

where

N is the number of data points in wind speed bin k

$L_{\mathrm{j,k}}$ is the sound pressure level of measurement period j in wind speed bin k.

The type A standard uncertainty on the average sound pressure level in wind speed bin k $s_{L_{\mathrm{k}}}$ is calculated by Equation (2):

$$s_{L_{\mathrm{k}}} = \sqrt{\left(\frac{\sum_{j=1}^{N}\left(L_{\mathrm{j,k}} - \bar{L}_{\mathrm{k}}\right)^2}{N \cdot (N-1)}\right)} \tag{2}$$

where

$\bar{L}_{\mathrm{k}}$ is the average sound pressure level in wind speed bin k from equation (1)

The combined type B standard uncertainty on the energy averaged sound pressure level $u_{L_{\mathrm{j}}}$ for each measurement period, j, is calculated by Equation (3). Guidance for Type B uncertainties is given in Table 3:

$$u_{L_\mathrm{j}} = \sqrt{\sum_{q=1}^{4} u_{L_\mathrm{j,q}}^2} \tag{3}$$

where

$u_{L_\mathrm{j,q}}$ is the type B standard uncertainty from source q on the average sound pressure level for each measurement period j.

The type B standard uncertainty on the average sound pressure level in wind speed bin k u_{L_k} :is calculated by Equation (4)

$$u_{L_\mathrm{k}} = \sqrt{\left(\frac{1}{N}\sum_{j=1}^{N} u_{L_\mathrm{j,k}}^2\right)} \equiv u_{L_\mathrm{j,k}} \tag{4}$$

where

$u_{L_\mathrm{j,k}}$ is the combined type B standard uncertainty on the average sound pressure level for each measurement period j, see Equation (3). This value is the same for all values of j.

The combined standard uncertainty on the average sound pressure level in wind speed bin k $u_{\mathrm{com},L_\mathrm{k}}$ is calculated by Equation (5):

$$u_{\mathrm{com},L_\mathrm{k}} = \sqrt{s_{L_\mathrm{k}}^2 + u_{L_\mathrm{k}}^2} \tag{5}$$

This applies to the background sound measurements as well.

The background corrected sound level and uncertainty on the background corrected sound level can be calculated as:

$$L_\mathrm{c,k} = 10 \cdot \log(10^{\left(\frac{L_\mathrm{T,k}}{10}\right)} - 10^{\left(\frac{L_\mathrm{B,k}}{10}\right)}) \tag{6}$$

$$u_\mathrm{c,k} = \frac{\sqrt{\left(u_{\mathrm{com},L_\mathrm{T,k}} \cdot 10^{\left(\frac{L_\mathrm{T,k}}{10}\right)}\right)^2 + \left(u_{\mathrm{com},L_\mathrm{B,k}} \cdot 10^{\left(\frac{L_\mathrm{B,k}}{10}\right)}\right)^2}}{10^{\left(\frac{L_\mathrm{T,k}}{10}\right)} - 10^{\left(\frac{L_\mathrm{B,k}}{10}\right)}} \tag{7}$$

Table 3 – Examples of possible values of type B uncertainty components relevant for apparent sound power spectra

Component	Possible typical range	Possible typical standard uncertainties
Calibration, u_{B1}	±0,3 dB	0,2 dB
Instrument, u_{B2}	±0,5 dB	0,3 dB
Measurement position, u_{B3}	±0,5 dB	0,3 dB
Wind screen insertion loss, $u_{B4;}$	±0,3 dB	0,2 dB

10.3.3 Calculation of average values and uncertainty per bin based on measurements – Arithmetic averaging

The average value, $\bar{X}_k$, is calculated by Equation (8):

$$\bar{X}_k = \frac{1}{N}\sum_{j=1}^{N} X_{j,k} \tag{8}$$

where

N is the number of measurements in wind speed bin k

$X_{j,k}$ is the value of X of measurement period j in wind speed bin k

The type A standard uncertainty on the average value of X in wind speed bin k is s_{X_k} which is calculated by Equation (9):

$$s_{X_k} = \sqrt{\left(\frac{\sum_{j=1}^{N}\left(X_{j,k} - \bar{X}_k\right)^2}{N \cdot (N-1)}\right)} \tag{9}$$

where

$\bar{X}_k$ is the average value of X in wind speed bin k from Equation (8)

$X_{j,k}$ is the value of X measurement period j in wind speed bin k

Type B uncertainties are not relevant for relative measurements like AM and tonal audibility.

10.3.4 Calculation of average sound pressure level and uncertainty per bin when using the sound power level based regulatory scheme

The sound power level based regulatory scheme is based on sound power levels determined through measurements according to IEC 61400-11. The method provides the sound power level and uncertainty per bin.

When predicting the sound level at a receiver position the uncertainty is based on the uncertainty of the sound power level of each source (wind turbine), the prediction model and the modelling.

The uncertainty on the predicted sound pressure level can be estimated by

$$u_{L_{\mathrm{A,k}}} = \frac{\sum_{i=1}^{N}\left(u_{\mathrm{LWA,i,k}}10^{\left(\frac{L_{\mathrm{pA,i,k}}}{10}\right)}\right)}{\sum_{i=1}^{N}10^{\left(\frac{L_{\mathrm{pA,i,k}}}{10}\right)}} \tag{10}$$

where

$L_{\mathrm{A},i,\mathrm{k}}$ is the sound pressure level from wind turbine number i and

$u_{\mathrm{LWA},i,k}$ is the uncertainty of the sound power level of wind turbine i and wind speed bin k.

NOTE The standard uncertainty of the prediction model is expected to be 2 dB for both ISO 9613-2 and for Nord2000 for downwind propagation for wind turbine sound up to 3 km to 5 km.

The uncertainty contribution from sound propagation modelling is estimated to 0,5 dB.

$$u_{\mathrm{com},L_{\mathrm{k}}} = \sqrt{u_{L_{\mathrm{pAk}}}^2 + u_{\mathrm{prediction\ model}}^2 + u_{\mathrm{modeling}}^2} \tag{11}$$

11 Sound pressure level

11.1 Outline

The purpose is to determine the sound pressure levels of the wind turbine or wind farm sound at the receptor position. Measurement methods are outlined in Clause 11 that cover long-term, short-term, and modelling based approaches determining the sound pressure level at the receptor position. It is acknowledged that local regulations and guidelines often describe the intended method for such measurements with varying degrees of detail. It is anticipated that this document could be used either by authorities in outlining appropriate methods for a given jurisdiction, or by measurement institutes in interpretation of local regulations and requirements, or in research efforts where quantifying the sound pressure level in the far-field location is desired.

Generally, the preferred method to measure the sound pressure level at a far-field location is with long term measurements. This method allows for evaluation of the in-situ acoustic field that occurs during the desired atmospheric conditions. However, it is acknowledged that the other methods outlined here can also be used to make sound scientific conclusions about the sound pressure level at the receptor location.

11.2 Instrumentation

For standard requirements for determination of sound pressure levels, see 6.1.2 and 6.1.3.

For standard requirements of audio recording and playback systems, see 6.1.6.

For standard requirements for the necessary meteorological measurement systems, see 6.2.

11.3 Acoustic measurements

11.3.1 General

The main acoustical quantities to be measured are the equivalent sound pressure level, L_{Aeq}, or statistical level, L_{Axx}. These data are obtained by determining the appropriate quantities in short measurement intervals such as between 10 s and 10 min to be able to determine measurement validity, and subsequently aggregated into longer periods to correspond with the intended analysis.

The appropriate interval time for each measurement can depend on the intended outcome, the measurement index being computed, and the expected variability of the data. Subclause 11.3 outlines considerations and measurement interval times.

11.3.2 Equivalent continuous A-weighted sound pressure evel, L_{Aeq}

When measuring L_{Aeq}, the acoustic energy within an interval is energy averaged. Because of the nature of the energy averaging, the resulting levels tend to be more influenced by higher sound levels occurring during the interval. Consequently, L_{Aeq} are more susceptible to contaminating transient sound events. For this reason, measurement intervals should be chosen to be shorter intervals, such as 1 min, but not shorter than 10 s, in order to isolate the contaminating transient event within an interval that can then be discarded.

11.3.3 Statistical level, L_{Axx}

Statistical indices allow for some level of automatic reduction of the influence of transient events in the data. They can thus be used with longer interval times than L_{Aeq} levels. Statistical indices such as L_{Axx} sound levels are typically analysed in 10 min intervals. It is recommended to keep the maximum interval length for all indices to 10 min given potential variability in wind speeds. The parameter basis, the period of logging and the class interval used to determine the $L_{N,T}$ shall be reported.

Statistical indices can be useful in improving the quality of a data-set, for example to identify outliers or similar, when paired with short L_{Aeq} intervals. For example, a large difference between an $L_{A90}/L_{Aeq}/L_{A10}$ could indicate a volatile sound level within a short interval and identify a contaminated interval. See Annex F for examples.

Care should be taken in regulatory environments where the limits are described in statistical indices to ensure that appropriate interval times are used and handling of contaminated of data is appropriate. When comparing different statistical indices, it should not be assumed that the relationship between them is stable. Any computation with different indices should be done with care. Statistical indices for shorter periods cannot be logarithmically averaged or summed to replicate the same statistics for longer periods.

11.4 Non-acoustic measurements (SCADA, wind speed, temperature, humidity)

For the duration of the campaign, SCADA data for the acoustically relevant wind turbines will be recorded. The SCADA data requirements are outlined in 9.2. To the extent possible, the SCADA data intervals shall match the intervals of the A-weighted sound pressure levels. Refer to 6.5 for guidance on time synchronization.

At or near the acoustic receptor location, the wind speed, wind direction, and precipitation shall be recorded. A representative location should also collect temperature, barometric pressure and humidity for the measurement area (of each receptor location). The wind speed and wind direction data intervals should preferably match the intervals of the A-weighted sound pressure levels. It is recommended that the testing requirements be determined using the outline and guidance provided in 7.2.

11.5 Data processing and analysis

11.5.1 Data requirements

Subclause 11.5 outlines the data requirements in order to determine receptor location that can be attributed to a wind power facility during the relevant operating conditions of the facility. It is anticipated that this will aid in determination of details regarding how the below quantities should be derived, the placement of the relevant sensors, synchronization of the data, and sensors required to determine representative operational conditions of interest.

The following quantities should be determined as required for the analysis at relevant intervals (see Table 4):

Table 4 – Quantities as required for analysis

Quantity description	Comment
Receptor location:	
Sound pressure level	See Clause 11
Wind speed	See 9.3
Wind direction	See 9.4
Temperature	See 9.6
Humidity	See 9.6
Precipitation level	See 9.5
At wind farm infrastructure for relevant wind turbines:	
Wind turbine electrical power, yaw angle, rpm	See 9.7
Wind direction at hub height	See 9.4
Wind speed at hub height	See 9.3
Optional: cloud cover	See Annex K

11.5.2 Data binning

When binning of the measurements is required, the procedures shall follow the methods outlined in 10.1. The method applies to all wind speeds and directions. The wind speed range for documentation is related to the specific intent of the measurement purpose and could be set by local guidelines.

11.5.3 Handling extraneous sound data

It is anticipated that during the measurements, transient conditions can influence the sound levels. As such it is appropriate to remove data influenced by intermittent, extraneous sound sources. This should be applied equally to ON and OFF conditions. Examples of such extraneous sound sources could be:

- variable traffic;
- rivers and roads after rainfall;
- seasonal birds (dawn chorus) and insects.

Some strategies for removing extraneous sound are provided in Annex F.

11.5.4 Determination of representative conditions

The gathered data will be time filtered to create one or more data-sets, representative of the times of interest (noting that some data can fall into multiple data-sets or none). The times of interest should be determined in the measurement plan outlined in 7.2, with consideration for the purpose of carrying out the sound pressure level measurements.

Examples of measurement plans are provided in Annex D.

11.6 Measurement methods

11.6.1 Long term measurements of wind turbine operation without shut down

This method is intended for a situation in which compliance can be checked at receiver locations using simple measurements. There are limitations to the usefulness of this method. However, it can be used to provide a satisfactory level of information for regulators in certain conditions. It could be useful in scenarios of high wind shear where the hub-height wind speed is high enough for the wind turbines to be operating and the ground level wind speeds are low, reducing the amount of background sound contribution.

In concept, this method involves conducting measurements with the wind farm operating in the desired state (for example, over a specific, desired wind speed range, or at or close to its maximum sound power output), while also being in a condition where background sound levels are kept at a minimum. The measurements can be compared against the regulatory limit, and be used to confirm compliance, if the levels fall below the allowed limit. If the measured levels are above the allowable limit, no conclusion can be made regarding compliance, as the significance of the contribution to the measured levels from the background sound is not known during the measurements. In the latter case, measurements during wind turbine shutdown would be necessary to make an assessment of compliance.

This method is applicable to any acoustic indicator (L_{eq}, L_{90}, L_{50}) that the regulator would require. Minimum data requirements are recommended to be established before measurements are conducted and should be determined with respect to the acoustic index being measured.

During the course of the measurements, if background sound is considered to have a significant and measurable contribution to overall sound levels, the background levels should be measured and quantified. Acoustic data is considered to represent background sound where the relevant wind turbines are confirmed not to be producing a significant amount of sound for the entirety of the measurement interval. Selection of relevant wind turbines shall be the same for background sound determination as for the wind speed determination (see 9.3.2.3). This may be confirmed by evaluating the power output and rpm of the relevant wind turbines.

11.6.2 Short term measurements including periods of wind turbine operation and shut down

This method may be incorporated as part of an overall measurement program to provide another line of evidence as to the sound level attributable to the project. This method can allow for the quantification of the wind turbine sound and the background sound during a specific timeframe provided the conditions do not materially change between the on and off period. Measurements would be carried out on a continuous basis and the wind farm would be temporarily stopped (including any auxiliary sound-emitting equipment) for short durations (e.g. 30 min to 1 h). Comparisons of sound levels between operational and shut down periods would be used to determine the contribution of the wind farm at the measurement location. The comparisons would only be possible between periods measured within short timeframe such as 3 h to 4 h.

This method relies on the assumption that environmental conditions, which have an influence on the acoustic performance, have not changed substantially between the periods of wind turbine operation and wind turbine shut down being compared. This specification provides guidelines and limitations to ensure that the comparisons are appropriate. If the conditions are deemed comparable, then the sound pressure level contribution can be calculated as a logarithmic energy subtraction of the background sound levels, during the turbine shut down, from the total sound levels during the operational periods.

In carrying out this method, operational and shut down periods should be compared on a case-by-case basis, and a determination has to be made whether conditions have materially changed between the turbine operation and shut down periods or not. If the operational and shut down periods are deemed to not be sufficiently comparable, a comparison and subsequent logarithmic energy subtraction cannot be carried out. Other than the elapsed time between the turbine operation and shut down periods, several other factors could determine validity of the comparison such as (but not limited to):

- representative conditions of interest (see 7.3);
- characteristic wind direction (see 9.4);
- atmospheric stability, in particular avoiding changes from day to night or night to day;
- significant changes of cloud cover, temperature gradient, wind shear (or other quantities indicating a change of atmospheric stability and thus sound propagation or wind induced background sound levels);
- extraneous sound sources (traffic noise, farming sound, sound by humans or animals, etc.).

It is recommended that the acceptable range of conditions for validity of this method be pre-determined in the testing plan and applied to the data once the measurement campaign begins. For example, generally, the time between periods of turbine operation and shut down should not be more than 3 h to 4 h to ensure comparable conditions.

Although not explicitly required, data gathered in this fashion can be binned by wind speed or wind direction for a binned analysis methodology to account for variations in conditions during the measurement. If conditions are expected to be unsteady and fluctuating, more frequent stopping of the turbines can be prudent, and a bin analysis likely to be necessary.

11.6.3 Long term measurements including periods of wind turbine operation and shut down

This method is similar to short-term measurements (see 11.6.2), but it typically utilises un-attended long term measurement stations, and continues measurements both during wind turbine operation and wind turbine shut down over much longer periods (several days, weeks, or months). This is expected to result in a larger data-set. Depending on the test plan, it could be used to target a much larger range of different operating and environmental conditions. These variations are captured and binned for appropriate data handling, for instance, larger wind speed ranges as well as a range of different wind directions, under different atmospheric stability parameters and thus sound propagation characteristics. As such, the method allows for more wide sweeping statements about the sound pressure level attributable to a wind farm at a given location.

In order to achieve the intended results, care shall be taken to ensure that environmental conditions are comparable between turbine operation and shut down periods. For instance, both data-sets shall comprise periods covering the same times of day, same range of meteorological conditions, etc.

While wind turbine sound emission does not change with season (although certain conditions affecting wind turbine operation can occur more or less frequently on average in different seasons), background sound can change significantly (wind induced sound in trees with versus without leaves, animal sound like birds, insects, frogs, etc.). Thus, the timing of the testing should consider acoustic influence from ambient conditions, as well as ensuring that over the timeframe of the measurement significant seasonal changes to the background sound levels do not occur.

Measurements of sound levels during wind turbine operational and shut down are required to be part of a continuous and contiguous data-set (allowing for short gaps due to unforeseen equipment issues etc.). Shut down, or other background sound measurements, made as part of prior measurement campaigns cannot be combined with a new operational measurement campaign.

Once sufficient data is collected, data reduction shall be carried out to exclude transient extraneous sound events (see 7.4), and to filter for conditions deemed representative (see 7.3). The data is then binned (see 10.1) by wind speed and wind direction. The acoustic descriptors for each bin are determined using the appropriate averaging of the data within the bin. The wind farm acoustic contribution can then be determined by logarithmically subtracting the resulting background sound level, measured during turbine shut down, from the total sound level, measured during turbine operation from the same bin.

11.6.4 High background sound situation

Where background sound levels are high, a correction for the influence of background sound is not possible. Where the determination of compliance with assessment criteria therefore is in question, an alternative measurement and analysis approach is required, for example via measurements of sound power level at the turbine in the near-field for use in a reliable prediction model (see 11.8), or measurements at a proxy location (see Annex I). A proxy location requiring a prediction of comparative sound levels to correct the measured results to the location being represented by the proxy should be the least preferable method as this introduces both the higher measurement uncertainties of a receptor distance method with the uncertainties related to the use of a prediction model.

Note that the sound power level and proxy location measurements are only applicable for sound pressure level estimation, and cannot be used for the assessment of sound characters in line with Clause 12 and Clause 13.

11.7 Guidance on background sound correction

To determine the specific wind turbine sound levels, the total sound is corrected for the influence of the background sound.

Background sound data shall be binned in the same manner as the wind turbine operational sound. Depending on site conditions, it can be appropriate to filter the background intervals for the same shear conditions as the wind turbines in operation, i.e. an additional filter such that the hub height wind speed during the background measurements is similar to the wind turbine in operation measurements.

Generally background sound correction is done using the total sound levels from each bin using a logarithmic subtraction between the total sound and the background sound. Care should be taken when the difference between the total and background sound levels is less than 3 dB.

- If (bin averaged) total sound is at least 3 dB higher than shut down sound, a logarithmic background sound correction can be applied.
- If (bin averaged) total sound is between 0 dB to 3 dB higher than shut down sound, it is suggested to use a correction of 3 dB.

Noise levels with spurious data shall be removed or otherwise adjusted in the same way as the total sound case. It should be noted that individual extraneous sound events can be more pronounced during shut down conditions. Removing these extraneous points shall not be more restrictive in background periods (wind turbine OFF) compared to total sound (wind turbine ON) periods. Guidelines and examples of methods for removing extraneous sound are provided in Annex F.

NOTE 1 If the difference between measured total sound and background sound is less than 3 dB, an excess of regulatory noise limits (violation) cannot be found owing to the in-built uncertainty of the measurement concept.

NOTE 2 If the overall sound level is less than the regulatory requirement, a finding of compliance can be possible.

11.8 Sound power level based regulatory scheme

11.8.1 General

Conducting accurate sound immission measurements at large distances from a sound source can often become complicated or impractical due to the local ambient conditions. As the distance between the source and microphone position increases, the signal is weakened, and eventually is contaminated by background sound levels present at the microphone position to a degree where it is not possible to obtain meaningful results for the wind farm sound. The sound pressure level existing at a specific point far from the wind turbines can be estimated using a combination of near-field measurements for determination of the apparent sound power level and sound model propagation. In such a scenario, the apparent sound power level of the wind turbines could be determined using the methods outlined in IEC 61400-11 describing sound power level determination and used as inputs to a sound propagation model. In the case of multiple wind turbines on a site, the following procedures are recommended:

- If the sound power level of a wind turbine has been measured, the measured L_{WA} will be used in the model for that wind turbine.
- If the sound power level of a wind turbine has not been measured, either the arithmetic average or energetic average dependent on local regulation for L_{WA} of the measured sound power levels of the wind turbines of the same type, same configuration and the same operational mode from the site or the specified sound power performance will be used, whichever is higher. Consideration should be made for uncertainty factors in the specified sound power levels in order to ensure comparable sound inputs are used in the model.
- For large wind farms the set of sound relevant wind turbines can be selected for investigation of the sound power levels representative for the wind farm. The wind turbines for testing could be selected from the sound relevant wind turbines for each receptor location.

Once the inputs to the model have been determined, a sound model can be used to arrive at the sound pressure levels expected at the immission point. Currently, there are multiple modelling standards that are commonly used for wind turbine sound. It is important that sound modelling parameters that reflect appropriate assumptions for wind turbine sound are used. The following parameters are recommended for sound modelling of the two preferred methods.

11.8.2 ISO 9613-2

This sound modelling standard is an octave-based method and requires sound power levels in octave band data from 63 Hz to 8 kHz. The method is considered an engineering model owing to the limitations with respect to elevated sources and meteorology. It has been widely used for wind turbine sound, and has been found to be reasonable if the following parameters are used (see Table 5):

Table 5 – ISO 9613-2 modelling parameters

Parameter description	Parameter value	Comment
Source height	Hub height	Point source
Directivity	Omnidirectional	Apparent sound power level
Ground factor	No more than 0,5	Different regulatory schemes require different values
Temperature, °C	10	15 °C most conservative
Relative humidity, %	70	80 % most conservative
Receptor height, m	4	Reducing the influence of the ground
C_{met}	0	

It has to be understood, that parameters like relative humidity, temperature and/or ground factor have not been chosen because they are a mean value for the site or country, but because they show best agreement in comparison with measured values at receptor position.

Many jurisdictions have specific parameter ranges for use in sound modelling for wind turbines. Local regulations can apply when making sound predictions using such a model. The above parameters are recommendations when local guidance is not available.

Different software implementations have options to limit the size of the area included in the calculations or simplify calculations for low levels of the resulting sound. It is important to ensure that this type of limitations are set at the right level to get correct results.

The method of calculating the ground effect is based on a scenario with ground which is approximately flat, either horizontally or with a constant slope. Some investigations have found that concave ground profiles (propagation over a valley) can result in lower levels of ground attenuation. A correction of –3 dB is applied in all frequency bands if the ground falls away significantly between the source and the receiver, such that the mean propagation height h_m is at least 50 % more than that over flat ground. However additional investigations are necessary to confirm the relation between concave ground profile and ground attenuation.

11.8.3 Nord2000

This is a 1/3-octave band model and requires sound power levels in 1/3-octave bands from 10 Hz to 10 kHz. When using the Nord2000 model for prediction of wind turbine sound, the following parameters are recommended (see Table 6):

Table 6 – Nord2000 modelling parameters

Parameter description	Parameter value	Comment
Source height	Hub height	Point source
Directivity	Omnidirectional	Apparent sound power level
Ground factor	Land, typically D or E Offshore, G	Flow resistivity 200, 500 20 000 kNms^{-4}
Temperature, °C	10	15 °C most conservative
Relative humidity %	70	80 % most conservative
Pressure millibar	1013,3	
Terrain	Use terrain profile as it is from elevation lines or similar	
Wind speed, m/s	8 m/s at 10 m height with maximum sound power level or wind speed distribution	Typical authority requirement
Temperature gradient C/m	0	Unless specific knowledge or requirement is available
Turbulence (wind) m(4/3)/s^2	0,120	Unless specific knowledge or requirement is available
Turbulence (temperature) K/s^2	0,008	Unless specific knowledge or requirement is available
Roughness length, m	Actual roughness length	Or recalculate from measured wind shear for specific sites or situations.
Roughness class	Small, 0,25	Not very important
Wind direction	Downwind? or measured wind direction profile?	Typical authority requirement
Receiver height, m	Use the physically correct value, for example 1,6 m above ground	Dependent on authority requirement
Different software implementations have options to limit the size of the area included in the calculations or simplify calculations for low levels of the resulting sound. It is important to ensure that this type of limitations are set at the right level to get correct results. See 10.3 for uncertainty of different models.		

11.9 Reporting of results

The following data shall be reported in binned values where applicable:

- sound pressure levels:
  - total sound,
  - background sound,
  - specific wind turbine sound,
- power;
- wind speed;
- wind direction;
- other binned parameters;
- scatter plot of measured sound pressure levels versus binning wind speed;
- time series plots of measured sound pressure levels, power, wind speed, wind direction;
- measured sound power level data for prediction models; input parameters for prediction models.

12 Tonal audibility

12.1 Outline

The purpose of Clause 12 is to describe how to determine the tonal audibility of wind turbine or wind farm sound at a receptor location based on standardised methods. The presence of tones in the sound at different wind speeds and wind directions shall be determined based on narrowband analyses.

Sound with audible tones is perceived as more annoying than the same sound without tones. To be able to evaluate the effect of tonal audibility in the sound it is necessary to have a method that presents objective results for the tonal audibility that corresponds to the subjective perception, and which is suitable for use on large data-sets in a semi-automated manner. In this document, ISO/TS 20065 (henceforth referred to as the 'ISO method') has been selected as the basis for evaluation of the tonal audibility of the sound from wind turbines. Clause 12 details an implementation of the ISO method for the analysis of wind turbine sound measured at receptor distances.

The most prominent tones can be measured in wind directions other than downwind of the most audible turbines, in part due to the lower aerodynamic masking sound in those directions. Hence it should be noted that analysing tonal audibility in purely downwind conditions, might not encompass the worst tonal audibility a resident can perceive.

The analysis should be carried out as per the ISO method, except where Clause 12 specifies a clarification, or deviation as part of the implementation. The standard approach assumed is to determine tonal audibility for 1 min periods, based on the combination of the results for 20 individual 3 s averaged spectra.

NOTE 1 When coding or trying to follow ISO/TS 20065:2022, reference is made to ISO/TS 20065:2022, Figure D.1 to Figure D.4 alongside Clause 5, as information regarding the process is not always detailed fully in either the diagrams or the text alone.

NOTE 2 A sample program to determine audibility can be downloaded from http://standards.iso.org/iso/20065 This can be useful for validating proprietary analysis codes, however the variations from the ISO method detailed in this implementation will be borne in mind.

NOTE 3 Annex L details some aspects of the ISO method which require further investigation to be more thoroughly addressed in a future revision of this implementation.

NOTE 4 ISO TS 20065 states that the procedure has not been validated below 50 Hz.

12.2 Overview of the ISO/TS 20065 method

Below is a brief summary of the method:

1) 'Basic' narrowband spectra are merged to create 3 s average narrow-band spectra.
2) For each 3-s averaged narrowband spectrum:
   a) The frequency range is scanned for peaks which could be potentially audible tones.
   b) Each line is checked whether it is both greater than the lines either side, and above the mean narrow-band level, L_S, within the critical band about the line (calculated through an iterative process).
   c) For each peak identified as a potential tone:
      i) a critical band is formed around the peak;
      ii) tone level, L_T, (including neighbouring tone lines) is determined if the spectral line identified as a potential tone is greater than the mean narrow-band level, L_S, (calculated through an iterative process assigning lines as either tone, masking or neither) about the tone line by at least 6 dB;
      iii) the tone is checked for distinctness;
      iv) the critical band level, L_G, of the masking noise, and the masking index, a_v, are calculated;
      v) The audibility, ΔL, is calculated by subtracting the critical band level, L_G, of the masking noise, and the masking index, a_v, from the tone level, L_T.
   d) For each tone identified:
      i) A critical band is centred around the maximum narrow-band level of the tone lines.
      ii) The critical band is checked to see if any other tones are present within the critical band.
      iii) Where other tones are found to be present (a frequency group), flag all spectral lines belonging to these tones and the tone under investigation.
      iv) Add the levels of the flagged spectral lines and, using the masking noise, L_G, and the masking index, a_v, of the participating tone with the greatest difference ΔL, to determine a ΔL of the frequency group.
   e) The decisive audibility, ΔL_j, is calculated for each narrow-band spectrum from the most prominent tonal audibility, possibly involving a frequency grouping.
3) Determination of mean audibility of multiple 3 s spectra is carried out through energy averaging.

NOTE The necessity for the calculation of the uncertainty of the tonal audibility is removed due to the implementation of the ISO method detailed within Clause 12, which results in more than 12 basic narrowband spectra being merged to create each 3 s average narrow-band spectra.

12.3 Instrumentation

For standard requirements for determination of narrowband spectra, see 6.1.4.

For standard requirements of audio recording and playback systems, see 6.1.6.

Assuming an audio recording is used as the source for obtaining narrow-band spectra, the recording should use a dynamic resolution of 24 bits and sampling rate ≥ 12 kHz. As it is key to be able to audition specific periods to determine if tones are likely to come from the wind turbines (such as for investigating outliers in the results), it is suggested a similar quality of audio recording is made even if narrow-band spectra are being measured directly.

NOTE In some circumstances it can be necessary to make audio recordings with a higher sampling rate where higher frequency tones are of interest. See 12.5.2.4 for more details about determining frequencies of interest.

12.4 Acoustic measurements

Although it is useful to have the context of broadband levels for periods which are being analysed for tonal content, there is no specific requirement for acoustic parameters to be measured 'live', as it is most practical to calculate the narrowband spectrum from the recorded audio files, applying an A-weighting.

The narrowband spectrum should use a constant line spacing, Δf, of 2 Hz and a Hanning window as mandated in the ISO-method with a 75 % overlap. A source audio file of sampling frequency 12 kHz analysed with these parameters will result in a window width of 0,5 s, or 6 000 samples, and will result in 25 'basic spectra' being averaged to create each 3 s averaged narrowband spectrum. Where a higher sampling frequency audio file is used as the source, the number of basic spectra per 3 s averaged narrowband spectrum will be higher.

12.5 Non-acoustic measurements

12.5.1 General

The wind speed and wind direction should be determined as per 9.3 of this document for each 1 min period. If a period other than 1 min is being used for the major time frame reference, the 1 min tonal audibility results should be assigned the wind speed and wind direction values for that larger time frame reference for all 1 min periods included within the larger time frame reference.

12.5.2 Implementation specifics

12.5.2.1 Wind turbine operation

Where wind turbine shut downs have been carried out during the measurements, the analysis should be carried out for wind turbine on and wind turbine off periods separately, and both data-set results reported.

NOTE It is not necessary to carry out rigorous tone origin investigation for turbine off data, however it is relevant to calculate and report tonal audibilities over the same tonal search range as the on data.

12.5.2.2 Frequency range of application

As wind turbine tones can occur below 50 Hz, and these tones can be perceptually audible, the method should be applied for all suspected or identified tones from 30 Hz upwards. To accommodate this, the critical band for tones between 30 Hz and 50 Hz should be fixed at 20 Hz to 120 Hz.

It can, in some circumstances, be desirable to investigate tones below 30 Hz, which could be done with suitable equipment and caution, but the implementation of this should be justified and treated with caution.

Tonal audibilities calculated for tones within the 30 Hz to 50 Hz region should be scrutinised carefully as there is the potential for A-weighting steepness to affect the assigning of lines as tone or masking, and can in some instances create the appearance of a tone that is not actually present. In addition perception within this region can vary more than at higher frequencies in practice.

In cases where tones appear at low frequencies it is advisable to investigate if the tone level is above the relevant hearing threshold (e.g. ISO 226 and ISO 28961). If the total tone level in a critical band is below the relevant hearing threshold, it can be reasonable to disregard the associated tones in the assessment of tonal audibility.

12.5.2.3 Critical bandwidth

Subclause 5.2 of the ISO method (ISO/TS 20065:2022) details how to determine the width of the critical band about a tone frequency. It is not clear from the ISO method whether corner frequencies (f_1 and f_2) should be rounded down, up, or to the nearest narrow-band line. For the purposes of this implementation, corner frequencies should always be rounded down to the nearest narrow-band line.

12.5.2.4 Determining frequencies of interest

It is highly likely that measurements carried out at residential locations will feature tones from sources other than the wind turbines under investigation. As such it is important to try and both limit the likelihood that tones from other sources will be analysed, and to scrutinise the frequencies of tones identified and to determine whether they originate from the wind turbines being investigated.

To reduce non-turbine tones from influencing the results, the first consideration is suitable positioning of the microphone (see Clause 8), however a further step is to limit the frequency range over which tones are searched for. It is suggested that the upper limit for the tonal search range should be based on the atmospheric absorption expected at the separation distance to the nearest turbine, calculated using ISO 9613-1. If the atmospheric absorption is at least 20 dB in a 1/3-octave band, tones are typically attenuated sufficiently to not be of concern by wind turbine neighbours. As the atmospheric absorption increases with frequency, if it can be shown that a specific 1/3-octave band will be attenuated by at least 20 dB, all 1/3-octave bands with higher frequencies will also be attenuated by at least 20 dB.

In Table 7 examples of the lowest 1/3-octave band to be attenuated by at least 20 dB are shown, and therefore an appropriate upper search frequency, for a range of distances, temperatures and relative humidities. The examples are calculated from ISO 9613-1.

Table 7 – Upper tone search frequencies based on a range of distance and meteorological conditions

Temperature (°C)	Relative humidity (%)	Distance (from source to receiver)			
		100 m (kHz)	300 m (kHz)	600 m (kHz)	1 000 m (kHz)
-10	100	10	5	3,2	2
0	100	10	6,3	4	3,2
10	50	10	5	4	2,5
10	80	10	5	2,5	2
20	50	10	6,3	5	4

This search range can be increased if tones above this frequency are suspected. Equally, the search range can be reduced further following either an initial analysis over the said range and the identification of turbine tone frequencies, or if the purpose of the analysis is to investigate a specific tone frequency from the outset. It can be useful to review IEC 61400-11 sound power level measurements, or to consult with manufacturers, in order to better understand any potential tone frequencies that could reasonably be expected from the turbine(s) under investigation. If an iterative approach is taken to determine the final search range, the results of both the wider and narrower search range(s) should be presented.

In addition, the frequencies of audible tones identified should be reviewed, and both common tone frequencies, and high audibility outliers, should be investigated to ensure tones from sources other than the wind turbine(s) under investigation are not affecting the results, and the details and extent of this documented in the report.

NOTE Determining the source of significant tones can be done via auditioning audio files, comparing turbine off and turbine on data, reviewing spectrograms and various other methods.

12.5.2.5 Criteria for a tone being present

For the purposes of this implementation, tones with calculated audibilities below 0 dB should not be excluded from the further calculation steps based on this criterion alone, and therefore should still be included in frequency grouping calculations (see below). This is likely a variation from what is intended within the ISO method as it is stated in the ISO method (ISO/TS 20065:2022) 5.3.8, Step 2: “If $\Delta L_k > 0$, then a tone is present”. This statement can imply that potential tones where $\Delta L_k < 0$ are in fact not tones.

NOTE The reasoning behind this divergence from the ISO method is that, although a potential tone with a $\Delta L_k < 0$ might not be audible by itself, the perceptual concept of a critical band (assuming the discrete two-tone case detailed below and within the ISO method is not met) is that all tone energy within a critical band is perceived as a single tone, and therefore all tone energy is summed to account for this. Whether the energy of a potential tone on its own would cause a perceptible tone is irrelevant to the underlying critical band concept.

12.5.2.6 Frequency grouping

Frequency grouping is the process of combining the energy of tones where multiple tones appear within a single critical band. This process is carried out after calculating the tonal audibility (from the combined energy of tone lines about the local maxima, and a subsequent correction for masking and distinctness check – see ISO method (ISO/TS 20065:2022), 5.3.8, Step 1 and Step 2) of each individual tone found to be present. This process is detailed in part within the ISO method (ISO/TS 60025:2022), 5.3.8, Step 3, and partly within the ISO method (ISO/TS 60025:2022), Figure D.4. This process was found to be commonly interpreted with small variations by practitioners, and therefore the clarifications below aim to avoid these variations from occurring.

This process should be carried out as follows for each audible tone (‘origin tone’) found in the ISO method (ISO/TS 60025:2022), 5.3.8, Step 1 and Step, in turn:

- A critical band should be centred on the line of the origin tone with the maximum tone level.
- The critical band should be searched on either side of the origin tone for other previously identified tones.
- Where another tone is found whose maximum tone level line falls within the critical band, all lines associated with this tone should be ‘flagged’ for inclusion within the frequency grouping (whether the individual tone lines, other than the maximum tone level line, fall within or without the critical band).
- Having searched the entire critical band, the origin tone and any other tones flagged should be compared to determine which tone has the maximum audibility calculated in Step 2, and this tone assigned as the ‘dominant’ tone.
- The tone lines of the origin tone and all other flagged tone lines should have their energy summed (ensuring no line is summed multiple times for adjacent tones), and then the tonal audibility of the frequency group calculated using this summed tone level and the masking corrections calculated in Step 2 from the dominant tone.
- The frequency assigned to this frequency grouping’s tonal audibility should be that of the dominant tone.

NOTE 1 The terms ‘origin tone’ and ‘dominant tone’ do not appear in the ISO method, but have been added here to try and aid clarity.

NOTE 2 Although in terms of reporting requirements, only the frequency and audibility of the decisive tone in each 3 s averaged spectra will be reported, more information can be useful for a more detailed analysis. It is suggested that storing the output of all individual (non-frequency grouped) tonal audibilities and associated frequencies (in line with Step 2) as well as the frequency grouping results is important for investigating results. Furthermore, where frequency groupings occur, it is useful for the practitioner’s analysis outputs to detail both the appropriate frequency for the frequency groups tonal audibility, and the frequencies of the tones combined within the frequency grouping.

12.5.2.7 Determination of mean audibility for each 1 min period

The mean audibility of the decisive audibilities of a group of 20 consecutive 3 s averaged spectra should be calculated, corresponding to a 1 min mean audibility. This should be done for each 1 min period.

This calculation should be carried out according to the ISO method (ISO/TS 60025:2022), 5.3.9, except for the adjustment of 3 s decisive audibilities, ΔL_j, < 0 dB to –10 dB. These audibilities should be left with their original negative value for the purposes of energy averaging.

NOTE Using 3 s averaged spectra as the basis of the tonal analysis, and then combining these spectra to derive a 1 min result, has the potential advantage of tracking both frequency and tonal audibility variation within a 1 min period, as opposed to using 60 s averaged spectra, where both frequency and audibility can be blurred, and the level of tonality potentially underestimated. This advantage can, in some circumstances, be significantly reduced by using the -10 dB audibility adjustment for 3 s spectra where decisive audibility is below 0 dB. This is particularly the case where a tone is varying in audibility near the assumed threshold where small dips in audibility (just below 0 dB) bring down the energy average disproportionately, with the result that the derived 1 min mean audibility represents the tonal audibility within the period to a lesser degree. Where strong tonalities are present, however, this variation from the ISO method makes little difference to the 1 min result.

12.5.3 Data binning

Following the calculation of 1 min mean audibilities for the data-set, these audibilities should be aligned with a 1 min average (or longer time reference if necessary) wind speed and wind direction, calculated as per 9.3 and 9.4. These 1 min data points should then be binned for wind speed and direction with a resolution of 1 m/s and 30° (integer/north centred respectively). An arithmetic mean audibility should then be calculated for each bin.

If additional wind direction bins are required, as determined in the test plan (see Clause 7), for the purpose of the analysis (such as downwind sector), the above procedure should be followed with these additional bin parameters also.

12.5.4 Uncertainty

Use the principles of 10.3 for uncertainty calculations by arithmetic mean.

12.6 Reporting

The reporting of results using this tonal analysis method shall include the following in addition to the information required by Clause 15 of this document:

- Description and justification of methods used to identify false-positives and false-negatives within the data and to remove extraneous sound sources, and details of the data excluded.
- Tables of sectoral binned results showing 12 columns of wind direction sectors of 30° width starting with a sector centred on North at ‘0’ (345 ≤ x < 15°) and rows of 1 m/s wide wind speed bins centred for wind speed on the integer values starting at ‘1’ (0,5 ≤ x < 1,5 m/s). The wind speed bin rows should be contiguous and cover the range of data available. These tables can require additional columns of desired wind direction sectors based on the test plan requirements. The following bin values should be presented in separate tables (note that some bins are likely to contain ‘-’ or ‘0’ values):
  a) arithmetic mean tonal audibility;
  b) number of 1 min data-points analysed (and not excluded);
  c) three tables showing the percentage of 1 min datapoints within the bin above:
    i) 0 dB tonal audibility
    ii) 4 dB tonal audibility
    iii) 9 dB tonal audibility

- Charts showing:
  a) frequency for the highest 3 s decisive audibility for each 1 min period versus wind speed (note it can in some cases be useful to also plot rotor or generator rpm on a secondary axis where this is suspected to be related to key tones);
  b) wind speed versus wind direction with:
     i) each non-excluded 1 min period, with each data-point coloured to show if the tonal audibility value for that 1 min period was x < 0 dB, 0 ≤ x < 2 dB, 2 ≤ x <4 dB, 4 ≤ x < 6 dB, 6 ≤ x 9 dB, 9 ≤ x < 12 dB and 12 dB ≤ x;
     ii) tonal audibility versus wind speed chart;
     iii) each 1 min period analysed (and not excluded) from all wind directions,
- Additional charts can include:
  a) either $L_{\text{Aeq,1-minute}}$ or $L_{\text{A90,1-minute}}$ versus reference wind speed for each non-excluded 10 min period, with each data-point coloured to show if the tonal audibility value for that 10 min period was x < 0 dB, 0 ≤ x < 2 dB, 2 ≤ x< 4 dB, 4 ≤ x < 6 dB, 6≤ x < 9 dB, 9≤ x < 12 dB and 12 dB ≤ x.

13 Amplitude modulation

13.1 General

Due to the rotational nature of most sound sources related to a wind turbine, there is usually a regular pattern of rising and falling amplitude in the sound emissions, which can be described as amplitude modulation. The time between these peaks and troughs (frequency of modulation) is related to the rotational speed of the rotor. Quantifying the amplitude modulation allows insight into the overall character of the sound and allows an estimation of the extent to which the noise impact might be greater than expected for steady sound with similar averaged broadband sound level.

13.2 Outline

Clause 13 defines the procedures to be used in the analysis and reporting of the levels of amplitude modulation emanating from (a) wind turbine(s) at receptor distances. Measurement, instrumentation and calibration requirements have been specified in previous clauses, as are non-acoustic measurements required to define the conditions being analysed. All parameters to be measured and reported are identified, as are the data reduction methods required for obtaining these parameters.

The method detailed within Clause 13 is an implementation of the UK Institute of Acoustics Amplitude Modulation Working Group Final Report [7][2]. The primary changes from the method detailed within the Final Report relate to more specific output requirements, and the use of worst-case results in each bin. The method has been detailed within Clause 13 in a more concise format than in the Final Report, with the removal of the decision-making context.

NOTE This method has been identified for inclusion at the time of publication given its robust development and successful deployment history. It is understood that other methods are under development.

2 Numbers in square brackets refer to the Bibliography.

Application of the method described in Clause 13 provides the average modulation depth for each 1 m/s and 30° wide wind speed and direction bin, referenced to an appropriate wind speed height as detailed in previous clauses. It can be appropriate, in addition to the aforementioned bin resolution, to combine these bins to create wider bins covering either downwind, crosswind (clockwise and anti-clockwise of downwind separately) and upwind, or other wind direction angles to investigate criteria defined as part of the measurement plan. The wind speed range required will likely also be detailed within the measurement plan, however it is not recommended to widen the wind speed bin resolution further than 1 m/s. There is no set required wind speed range suggested within this document.

The method applies to all wind speeds and wind directions, and it should be taken into account that the directivity of amplitude modulation emission will vary compared to other wind turbine source(s).

The method is applicable for a modulation frequency range of 0,3 Hz to 1,6 Hz and should be based on external free-field measurements.

13.3 Instrumentation

Standard requirements for determination of 1/3-octave band spectra and narrowband spectra. Standard requirements for audio recording systems.

13.4 Acoustic measurements

100 ms L_{Aeq} 1/3-third octave band measurements, audio recording for auditioning purposes.

13.5 Non-acoustic measurements

Wind speed and wind direction, rotor rpm if available.

13.6 Data reduction procedures

13.6.1 General methodology

Acoustic measurements are made in 100 ms L_{Aeq} on 1/3-octave bands from 20 Hz to 10 kHz as a minimum. Wind speed and direction are referenced to average 10 min values. Wind speeds relating to bin definition should be 1 m/s wide and integer centred (i.e. a 5 m/s bin is from 4,5 m/s to 5,5 m/s). Wind direction relating to bin definition should be 30° wide and centred on the bin value (i.e. a 30° bin is from 15° to 45°).

In outline, a Fourier transform is taken of band-limited time series data to determine the fundamental modulation frequency (which is expected to be related to the turbine blade passage frequency (BPF)) and the second and third harmonics. These components are then used to reconstruct a time series, which should relate only to wind turbine amplitude modulation, with the influence of background sources minimised. The modulation depth is then calculated following the method of [5], i.e. subtracting the L_{95} of the filtered time-series from the L_5.

The method involves the following stages:

- Sound is measured in short-term, 100 ms L_{Aeq} values in 1/3-octave bands. Three frequency ranges, or bands, are evaluated: 50 Hz to 200 Hz; 100 Hz to 400 Hz and 200 Hz to 800 Hz, and the results which exhibit the highest resulting levels of amplitude modulation (AM) are used.
- The fundamental length of the input sample to be assessed (the minor time interval) is 10 s.
- The hybrid reconstruction method is used to determine the AM value for each 10 s value.
- The values of AM measured by the metric in each 10 s interval are aggregated over a 10 min period (the major time interval) to provide a single value which is the AM rating for the 10 min period.

Implementation of the recommended reference method requires the use of specific bespoke computing routines using programming platforms.

A sample code developed alongside the IOAAMWG Final Report [7] is available, although this code might not reflect the entirety of the method outlined within Clause 13, and is not maintained or written by IEC. The code is available at https://sourceforge.net/projects/ioa-am-code/[3].

Although it is relatively complex, a degree of complexity is considered inevitable in a method that is sufficiently robust for determining compliance or non-compliance with specific thresholds or limits.

13.6.2 10 s methodology

13.6.2.1 Input data

13.6.2.1.1 Frequency band

At receptor distances the majority of the audible energy of the sound emissions emanating from wind turbines will be focused around a relatively limited frequency bandwidth (usually somewhere between 50 Hz and 800 Hz for larger wind turbines). The range of the frequency bandwidth will depend on several factors including the wind turbine dimensions, rotational speed, wind direction or orientation in relation to receptor, and separation distance. It is desirable to focus analysis on a limited frequency range to reduce the influence of background sound sources, and better align modulation results with perception. It is possible to scrutinise spectral data to identify the frequency range where modulated wind turbine sound is most prominent, but as this varies with the factors detailed above, it is generally more efficient to use the three frequency bands below in a systematic analysis, than to identify the dominant frequencies which are modulating for each period.

NOTE 1 It can be the case for some wind turbines, or in some circumstances that the frequency of the dominant modulating wind turbine sound is outside the three bands detailed below. In these cases one or more alternative frequency bands could be used to analyse the dominant modulating wind turbine sound, however the method can require careful handling as this is a departure from the standard method. For more details see Annex G.

The input data to the analysis should be A-weighted, band-filtered 100 ms L_{eq} values. The analysis should be done for three band-filtered frequency ranges, each encompassing seven 1/3-octave bands, with 1/3-octave band centre frequencies:

- 50 Hz to 200 Hz;
- 100 Hz to 400 Hz;
- 200 Hz to 800 Hz.

NOTE 2 It will be borne in mind that for the higher frequency ranges (starting at 200 Hz and 400 Hz), data can be more prone to corruption from other sources, such as bird calls, and the resulting spectra will be scrutinised more carefully. Similarly, the lower frequency range might be more affected by wind noise.

The 100 ms 1/3-octave bands should be either measured as A-weighted values or have the A-weighting corrections applied to each band as a post-processing step. The resulting A-weighted bands should then be summed (logarithmically) within each of the above frequency ranges of interest in order to obtain a band-pass filtered $L_{Aeq,100ms\ (BP)}$ signal.

[3] IOA AM code is an example of a suitable product available commercially. This information is given for the convenience of users of this document and does not constitute an endorsement by IEC of this product.

NOTE 3 While it is possible to post-process audio recordings to A-weight them and filter them over the frequency band of interest, this entails significant practical difficulties: high resolution audio recordings would be required, which have large storage requirements; post-processing requires specialist software and is generally not straightforward. Therefore, the preferred approach is to use directly logged 1/3-octave band L_{eq} values, centred between 50 Hz and 800 Hz, in 100 ms resolution, either A-weighted or with the A-weighting corrections applied in post-processing. L_{eq} 1/3-octave bands were chosen in preference to fast time-weighted 1/3-octave bands as the former are more precisely defined and allow summing up in the manner specified, and also leads to higher resulting AM values as they result in more pronounced peaks and troughs.

13.6.2.1.2 Modulation frequency

The method requires, as input, a range of modulation frequencies in which the main (or fundamental) modulation frequency is expected to be found. This assists in excluding apparent 'modulation' which is not related to the turbines. This main modulation frequency is usually related to the rate at which each blade passes a fixed point during its rotation, the BPF.

Knowledge of the turbine type and its possible rotational rates, or turbine operational (SCADA) data, can assist in defining this range. For example, for a three-bladed turbine rotating at 20 rotations per minute (rpm), the modulation frequency of interest would be a BPF = 3 x rpm / 60 = 1 Hz. In practice, the rotational rate can vary between turbines on a particular site and it might not be possible or practical (except maybe in the simplest cases) to define a single expected BPF for each 10 min analysis period based on operational data.

Therefore, it is effective to specify a modulation frequency range and to determine the highest modulation peak found within this range, usually based on the known rpm range of the turbine(s) being measured. For example, for a turbine operating between 12 rpm and 22 rpm, the corresponding BPF range would be 0,6 Hz to 1,1 Hz, and correspondingly a search range encompassing this with some tolerance would be appropriate. This range can be determined or refined in an iterative analysis based on initial results if required.

NOTE Although it will be expected that modulation frequency will follow the trend of the blade passage frequency, it is normal for the exact frequencies to vary somewhat between the two. This is often shown by a chart of frequency versus wind speed showing both modulation frequency and blade passage frequency, where the two will be slightly offset, although approximately parallel. In addition, it will be borne in mind that, if there is damage or pitch irregularities with a single blade, there can be modulation associated with the overall rotation frequency (blade passage frequency divided by 3 for a three-bladed wind turbine).

13.6.2.2 Valid data

The 100 ms samples should be separated into consecutive, non-overlapping 10 s blocks (the 'minor' time interval). There are 60 such minor time intervals in each major interval of 10 min.

A 10 s block will only be considered valid if not excluded for the following reasons:

- the 'prominence' ratio is less than four (automatic processing) (see 13.6.2.3);
- there are no local maxima within the expected modulation frequency range in the power spectrum;
- manually excluded for other reasons (according to the practitioner).

A representative rating for AM is derived using the 90th percentile[4] of the distribution of 10 s AM rating values calculated within each 10 min period. This value is only calculated over the distribution of valid 10 s blocks, and only if the 10 min period contains at least 50 % valid blocks. The number of valid 10 s blocks in a 10 min periods is referred to as the 'n' number.

As for any acoustic data analysis, the practitioner will retain the ultimate responsibility for selecting valid periods of data if there is any doubt as to their suitability. This can be done in practice by a combination of the methods outlined in Annex F.

4 The highest 10 % of the 10 s values analysed, which is the equivalent of the L_{10} for noise levels.

Note that standard practice is to perform exclusions of invalid results on a 10 min basis if extraneous sound sources or other factors have invalidated any of the 10 s blocks within that 10 min period. In the situation where there is a necessity to exclude individual 10 s blocks without excluding the entire 10 min period to which they belong, adaption of the primary will be required and this adaptation detailed and justified.

The practitioner should review the data for potential false-positives and false-negatives and detail and justify the methods used for this.

Where data analysis is carried out to investigate other acoustic characteristics as detailed in other clauses of this document, or by using other methods, any exclusions of data based on corruption, or similar, carried out for other purposes should be considered as potential exclusions for the purposes of AM analysis according to this method also.

13.6.2.3 Signal analysis – 10 s blocks

The following procedure should be carried out for each 10 s sample:

a) The time-series is de-trended using a 3rd order polynomial 'best fit'.

b) The discrete Fourier transform (DFT) is calculated and both the real and imaginary parts of the output are retained. No window function should be used in the transform (i.e. rectangular window). Furthermore, no padding should be applied to the input; therefore, the output will have a frequency resolution of 0,1 Hz. This also restricts the maximum modulation frequency that can be assessed to 5/3 or just below 1,7 Hz.

c) The power spectrum is calculated from the DFT output using the following equation:

$$S_{xx} = \frac{\left|F\{x\}\right|^2}{m^2} \tag{12}$$

where

$F\{x\}$ is the output of the DFT;

m is the number of samples in the time-series (100 in this case).

Care should be taken to ensure correct handling of the indices referring to the positive and negative frequencies in the DFT output. Given that the input to the DFT is real, the indices corresponding to the negative frequencies can be excluded in the calculation of the power spectrum. This will result in a power spectrum with half the magnitude, however this is of no great consequence as only relative levels are considered in the analysis of the power spectrum. However, indices corresponding to the negative frequencies will be required later when performing the inverse Fourier transform.

d) The highest peak (local maximum) is identified within the user-defined allowable range of fundamental modulation frequencies (e.g. between 0,4 Hz and 0,8 Hz, for example, see Figure 1). The frequency at which the peak is found is considered the fundamental frequency of modulation for the 10 s block which should usually correspond to the BPF. If there are no local maxima within the defined range, the 10 s block should not be analysed further and identified as 'prominence-failed' (pf) as it is considered that there is no significant AM.

e) The prominence of the peak at the fundamental frequency is calculated using the method below and compared to the prominence threshold value of 4:

   – The magnitude of the fundamental peak, L_{pk}, is taken as the amplitude of a single line in the power spectrum at the frequency of the peak.

   – The two lines either side of the peak are ignored.

   – The masking level, L_m, is taken as the linear average of two lines on each side of the peak (beyond those lines immediately adjacent to the peak).

– The prominence ratio, p_{am}, of the peak is calculated using:

$$p_{AM} = \frac{L_{pk}}{L_m} \tag{13}$$

If the prominence ratio is less than the prominence threshold, the 10 s block should not be analysed further and identified as ‘prominence-failed’ (pf) as this indicates that AM at the BPF could not be readily identified.

NOTE 2 The prominence threshold of 4 was arrived to by the IOAAMWG [7] following testing on a range of sample data-sets. There can be some circumstances where this value could be improved for a specific data-set, however the process of doing this is time consuming and can be complex, but could be carried out if desired and sufficient expertise was available.

f) For each harmonic (2nd and 3rd), determine whether or not to include the harmonic energy in the inverse Fourier transform using the following method:
   - Estimate the harmonic frequencies by multiplying the fundamental frequency by 2 or 3 (for 2nd and 3rd harmonics respectively).
   - If the line at this frequency is not a local maximum in the power spectrum, check N lines on either side for a local maximum (where N is one for the 2nd harmonic and two for the 3rd harmonic). If no local maximum is found, do not include this harmonic in the inverse transform detailed below. If more than one local maximum is found, the largest is chosen.
   - Assuming a local maximum is found for the harmonic frequency, two additional conditions shall be met for the harmonic to be included in the inverse transform, namely:
     - The peak to peak amplitude[5] of the time-series generated by performing an inverse transform with only the energy at the fundamental frequency shall be greater than 1,5 dB.
     - The peak to peak amplitude of the time-series generated by performing an inverse transform with only the energy at that specific harmonic shall be greater than 1,5 dB.
   - If any of the aforementioned conditions are not met, the energy at that harmonic should not be included in the inverse transform.

The inverse Fourier transform is performed in the following manner:

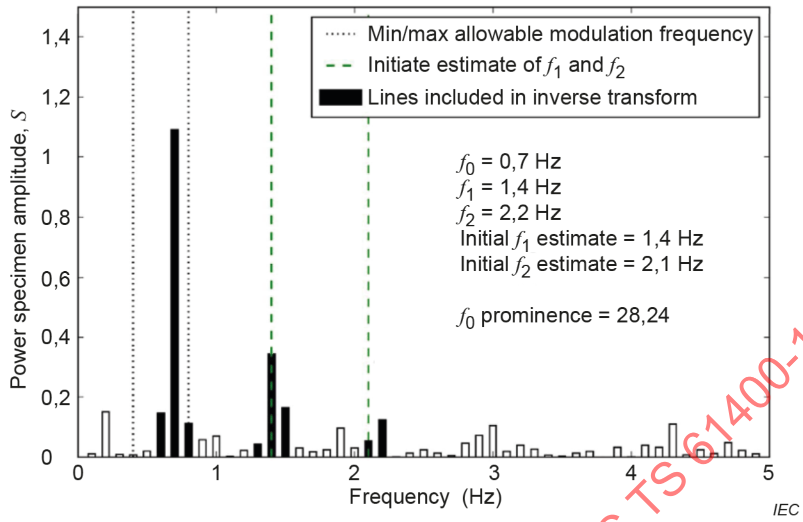
1) An array of zeros is created, the same size as the output from the DFT.
2) Take the index of the fundamental frequency identified in the power spectrum, along with one index on either side (totalling three lines), and insert the corresponding indices from the original DFT output (including real and imaginary components) into the corresponding indices of the newly created array of zeros. Repeat this for the indices of the corresponding negative frequencies.
3) Do the same for each harmonic identified for inclusion in the inverse transform (each time taking three lines centred on the harmonic frequency and also including the corresponding negative frequencies).
4) Perform an inverse Fourier transform on the newly created array, which should include components (from the original DFT output, complex numbers) only at the fundamental frequency and identified harmonics (three lines at each). The output of this transform should be real, without any imaginary part.

The output of the inverse Fourier transform will be a time-series resembling[6] the original time-series, but containing only energy relating to the identified frequencies.

5 Defined here as the maximum of the entire 10-second time-series minus the minimum of the same.

6 A useful verification check for any user implementing the procedure is to first include all lines in the spectrum and check that the result of the inverse Fourier transform is the same as the original (de-trended) time series.

The modulation depth for the 10 s block is calculated by subtracting the 5th percentile (L_{95}) of the reconstructed time-series from the 95th percentile (L_5) in the manner of [5]. This will tend to represent the highest typical modulation in the 10-s block.



NOTE The fundamental frequency, f_o, has been identified within the range of allowable modulation frequencies (marked as doted lines). Initial estimates of the frequencies of the second and third harmonics are shown as dashed green lines. The estimated frequency of the second harmonic, f_1, is a local maximum. The estimated frequency of the third harmonic is not a local maximum and the highest peak within two lines of the estimated frequency is identified as the true frequency of the third harmonic, f_2. Lines to be included in the inverse Fourier transform are marked (showing, in each case, the central line plus one line either side, i.e. three lines).

Figure 1 – Power spectrum for a 10 s block

The result of the 10 s analysis should be a modulation depth and frequency ("fundamental frequency of modulation") for each valid 10 s block. Non-valid 10 s blocks where the prominence criteria are not met (or no local maxima exist) should be identified as pf values.

13.6.3 Signal analysis – 10 min results

Each 10 min period consists of 60 consecutive 10 s blocks synchronised to line up on the hour precisely. For each frequency band (see 13.6.2.1.1):

- calculate the n number (number of valid 10 s blocks following prominence filtering);
- where the n number is greater than 50 % (30 valid 10 s blocks), calculate the 90th percentile of the valid modulation depths;
- where the n number is greater than 50 % (30 valid 10 s blocks), both the mean and mode modulation frequency should be calculated based on the n valid 10 s blocks for that 10 min period;
- where the n number is less than 50 % (30 valid 10 s blocks), a modulation depth value of 0 is assigned to that 10 min period, and no modulation frequency is calculated;
- align the modulation depth and modulation frequency values for that 10 min period with reference wind speed and wind direction to create a data-point.

13.6.4 Signal analysis – Binned results

For each frequency band (see 13.6.2.1.1):

- bin the data-points according to wind speed and direction[7];
- calculate the mean modulation depth for all data-points, including 0 values (but not including any excluded periods due to pf or other exclusions), for each bin.

For each bin, select the frequency band with the highest mean modulation depth and assign it to that bin. For each bin report the frequency band assigned, and the mean modulation depth using this frequency band, as well as the number of data-points within that bin and in brackets next to it the number of non-zero values within that bin.

It can be appropriate to combine these bins to create wider bins covering downwind, crosswind (clockwise and anti-clockwise of downwind separately) and upwind, or other wind direction angles, which can allow the reporting of results which are more likely to be statistically significant. These results shall be displayed in addition to the standard binning. The choice of representative frequency bands can be different for each of these wider wind direction bins.

It is not recommended to widen the bin wind speed further than 1 m/s.

NOTE The identification of meteorological conditions (bins) where higher levels of AM are not present is equally as important as identifying those where higher levels of AM are present.

13.6.5 Uncertainty

Use the principles of 10.3 for uncertainty calculations by arithmetic mean.

13.7 Reporting

The reporting of results using this AM analysis method shall include in addition to the information required by Clause 15 of this document:

- RPM range of wind turbines under consideration and resulting expected blade passing frequencies.
- Description and justification of methods used to identify false-positives and false-negatives within the data and to remove extraneous sound sources, and details of the percentage of data excluded.
- Tables of sectoral binned results showing 12 columns of wind direction sectors of 30° width starting with a sector centred on North at ‘0’ (345 ≤ x < 15°) and rows of 1 m/s wide wind speed bins centred for wind speed on the integer values starting at ‘1’ (0,5 ≤ x < 1,5 m/s). The wind speed bin rows should be contiguous and cover the range of data available. These tables can require additional columns of desired wind direction sectors based on the test plan requirements. These tables should show:
  a) For each frequency band, bin values (calculated according to 13.6.3 and 13.6.4) of:
     i) average modulation depth
     ii) number of 10 min data-points analysed (and not excluded)
     iii) percentage of datapoints above:
        - 3 dB modulation depth
        - 6 dB modulation depth
        - 9 dB modulation depth

[7] These bins should be 1 m/s and 30° wide, centred for wind speed on the integer values starting at ‘1’ (0,5 ≤ x < 1,5 m/s), and wind direction, starting with a sector centred on North at ‘0’ (345 ≤ x < 15°).

b) For the band in each bin or sector with the highest modulation depth:
   i) band (1, 2 or 3) with the highest modulations depth
   ii) average modulation depth
   iii) three tables showing percentage of datapoints above:
      - 3 dB modulation depth
      - 6 dB modulation depth
      - 9 dB modulation depth

c) Charts showing for each band:
   i) modulation frequency versus wind speed chart with two data series showing:
      - 10 min modulation frequencies (arithmetic mean and/or mode) versus wind speed
      - expected blade passage frequency versus wind speed
   ii) wind speed versus wind direction chart showing:

      each non-excluded 10 min period, with each data-point coloured to show if the AM value for that 10 min period was x < 1,5 dB, 1,5 ≤ x < 3 dB, 3 ≤ x < 4,5 dB, 4,5 ≤ x < 6 dB, 6 ≤ x < 7,5 dB, 7,5 ≤ x < 9 dB and 9 ≤ x
   iii) modulation depth versus wind speed chart showing

      each analysed (and not excluded) 10 min period from all wind directions

- Additional charts can include:

  Sound pressure level versus reference wind speed for each non-excluded 10 min period, with each data-point coloured to show if the AM value for that 10 min period was x < 1,5 dB, 1,5 ≤ x < 3 dB, 3 ≤ x < 4,5 dB, 4,5 ≤ x < 6 dB, 6 ≤ x < 7,5 dB, 7,5 ≤ x < 9 dB and 9 ≤ x.

14 Impulsivity

14.1 Outline

The purpose of Clause 14 is to determine the impulsivity of the wind turbine sound if the sound is considered impulsive.

Wind turbine sound is not typically considered to be impulsive. However, when occurring, impulsive sounds are usually originating from mechanical sources. Examples are banging sound like loose cables, yaw motors, loose glue in the blades, etc. Audible impulses shall not be confused with aerodynamic blade swish and thump sounds that are better described by the method outlined in Clause 13.

As impulsive sound is usually a sign of a defect or similarly it is not considered a part of the normal operation of a wind turbine. For that reason, a full description of impulsivity with respect to wind speed is not necessary. The situations where the impulsive sound occur can easily be identified and a (short) measurement can be made for these situations to identify the cause of the impulses.

The recommended method is the ISO/PAS 1996-3.

An impulse is defined as a sudden onset of sound, having a gradient that exceeds 10 dB/s for the total A-weighted sound. The prominence of the impulse also depends on the corresponding increase in the sound.

14.2 Instrumentation

Standard requirements are according to 6.1.2.

14.3 Acoustic measurements

Recording periods of 10 min are to be applied. This is a deviation relative to ISO/PAS 1996-3, that requests recording in 30 min periods, but shorter periods are recommended if relevant.

The prominence P_I of the impulses within each time period is determined as the highest prominence within that time period. Validation that the analysed sounds originate from the measured wind turbines shall be made by, for example, an audio recording of the analysed events.

14.4 Non-acoustic measurements

Since no correlation of the impulsivity with wind speed is required no requirement for measurement of non-acoustic parameters is required. However, the wind direction has to be from the wind farm to the receptor position within ±45°.

14.5 Data reduction

All recorded 10 min periods are analysed for impulsivity and the prominence P_I are presented in a table or a graph. The decisive value for the impulsivity is the highest value of P_I.

14.6 Uncertainty

The uncertainty on the calculated prominence is 0,3 dB in accordance with ISO/PAS 1996-3.

14.7 Reporting

Since detection of impulses is more of a diagnostic tool the results are not averaged and the results are given as the highest value of the prominence P_I for each 10 min period, highlighting the highest value.

15 Reporting

15.1 Information to be reported

15.1.1 General

The configuration of the wind turbine and its operating conditions shall be reported as follows.

15.1.2 Description of the test scope and measurement concept

- Description of the purpose of the measurement.
- The acoustical characteristics to be investigated.
- Noise limits or sound characteristic penalty to comply with, or both.
- Selected approach to fulfil the purpose of the measurement (including choices of instrumentation);

Optionally, if an agreed test plan exists in writing, it can be provided in the report as an appendix.

15.1.3 Characterization of the wind turbine(s)

The wind turbine configuration shall include the following information:

– Wind farm details:
  - name and location of the wind farm;
  - total nameplate capacity of the wind farm,
  - total number of wind turbines;
  - operational strategy of wind farm (e.g. curtailment strategy);
  - sound relevant wind turbines for each receiver position;
  - statement from operator to detail applied sound modes for wind farm or wind turbines during the measurements.

– Wind turbine details:
  - manufacturer;
  - model number;
  - rated power output;
  - hub height and rotor diameter.

– Operating details:
  - vertical or horizontal axis wind turbine;
  - upwind or downwind rotor;
  - passive stall, active stall, or pitch controlled wind turbine;
  - constant or variable speed;
  - power curve(s) in the modes for relevant wind turbines if required;
  - optionally, presence of blade add-ons or relevant wind turbine modifications.

15.1.4 Physical environment

The following information on the physical environment at and near the site of the wind turbine and the receptor locations shall be reported:

- details of the site including location, site map and other relevant information indicating receptor locations (microphone and/or met masts);
- type of topography or terrain (hilly, flat, cliffs, mountains, etc.) in surrounding area;
- surface characteristics (such as grass, sand, trees, bushes, water surfaces); optional estimated roughness length;
- distances to and descriptions of nearby reflecting structures such as buildings or other structures, cliffs, trees, water surfaces;
- other nearby sound sources possibly affecting background sound level, such as other wind turbines, highways, industrial complexes, airports;
- description of the sound environment at the time of measurement;
- photographs of the microphone position taken in the direction of the relevant wind turbines, and in the four cardinal directions;
- photograph of any other measurement equipment in the field if used (such as met mast).

15.1.5 Instrumentation

The following information on the measurement instrumentation shall be reported:

- manufacturer(s);
- instrument name and type;
- serial number(s);
- other relevant information (such as last calibration date);
- influence of secondary wind screen, if used.

15.1.6 Data

The following data shall be reported for the relevant wind turbines at the respective receptor locations:

- time and date of each measurement series;
- graphical time series of measured data, with as a minimum
  - measured acoustics properties;
  - wind speed;
  - wind direction;
  - excluded data;
- wind turbines operational and shut down;
- plot with wind speed versus wind direction detailing
  - filtered wind direction if applicable;
  - separate for each operational mode if applicable;
  - measured rotational speed versus power, optionally;
  - meteorological data (can include cloud cover, air temperature, air pressure, relative humidity);
- acoustic properties based on the relevant reporting requirements of the measurements.

Confidential parameter that can be provided for the assessment, shall not be reported.

15.1.7 Uncertainty

Report uncertainties according to Clause 11, Clause 12, Clause 13 and Clause 14.

Guidance for the assessment of measurement uncertainty can be found in Annex C and in ISO/IEC Guide 98-3.

Annex A
(informative)

Rating level

A.1 Rating of sound characteristics

The rating level comprises the equivalent continuous sound pressure level and adjustments for different characteristics of the sound. For wind turbines this is mainly tones, amplitude modulation and impulses.

Only one type of level adjustments should be applied at a time (the most severe):

1) $L_r = L_{eq} + K_T$
2) $L_r = L_{eq} + K_{am}$
3) $L_r = L_{eq} + K_I$

where

K_T is the adjustment for tonal audibility

K_{am} is the adjustment for amplitude modulation

K_I is the adjustment for impulsivity

The level adjustments are typically defined in local regulations. Examples are given below.

It is common practice to use level adjustments for the period of time of occurrence of the characteristic. For wind turbines this is more often related to wind speed, wind direction or the operation of the wind turbines than to the specific time of the day or year.

The main body of this document gives guidance on how to measure the sound characteristics as a function of wind speed, wind direction or the operation of the wind turbines. Thus, it is possible to calculate the rating level as a function of these parameters with the assistance of local regulations on level adjustments with guidance from standards.

A.2 Examples of adjustments to the determined sound pressure levels for tonal audibility

See Table A.1.

Table A.1 – Example of tonal adjustment K_T from the mean audibility ΔL

Mean audibility ΔL in dB			**Tonal adjustment** K_T in dB
	$\Delta L \leq$	0	0
0	$< \Delta L \leq$	2	1
2	$< \Delta L \leq$	4	2
4	$< \Delta L \leq$	6	3
6	$< \Delta L \leq$	9	4
9	$< \Delta L \leq$	12	5
12	$< \Delta L$		6
[SOURCE: ISO 1996-2:2017, Table J.1.]			

Due to the precision of the subjective assessment of sound, it is often more appropriate to use larger steps than 1 dB, for example 3 dB, that is:

$\Delta L \leq 2$: K_T = 0 dB

$2 < \Delta L \leq 9$ dB: K_T = 3 dB

$\Delta L > 9$ dB: K_T = 6 dB

A.3 Examples of adjustments to the determined sound pressure levels for amplitude modulation

See Figure A.1.

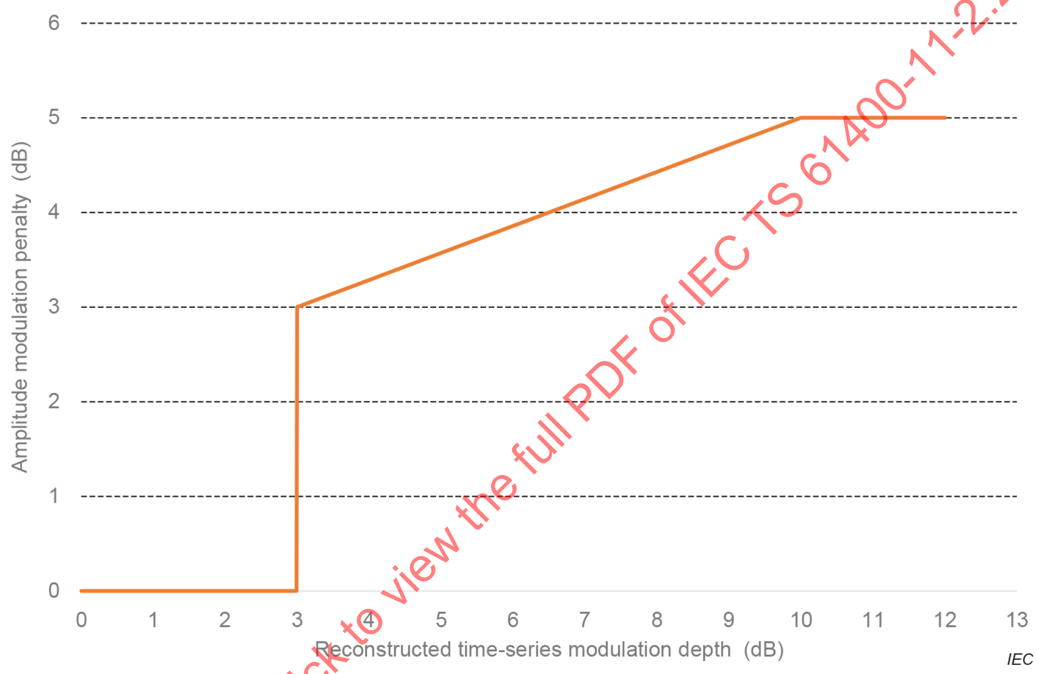


Figure A.1 – Examples of adjustments to the determined sound pressure levels for amplitude modulation

A.4 Examples of adjustments to the determined sound pressure levels for impulsivity

The following suggested adjustments for the existence of impulsivity are taken from ISO/PAS 1996-3.

For sounds with onset rates larger than 10 dB/s the following adjustment K_I, based on the predicted prominence P_I, can be applied:

$P_I > 5$: $K_I = 1{,}8 \cdot (P_I - 5)$ dB

$PI \leq 5$ K_I = 0 dB

It is proposed that this adjustment is made to $L_{Aeq,30min}$ on the basis of the one event with the highest value of P_I occurring during the 30 min period.

L_{Aeq} correction values K_I following ISO/PAS 1996-3 can be calculated for each binned result. It is recommended to subtract the calculated K_I uncertainty (0,6 dB according to ISO/PAS 1996-3 from K_I before comparison to any noise limits.

Annex B
(informative)

Infrasound and wind turbines

Infrasound is defined as sound in the frequency range from 1 Hz to 20 Hz. Sometimes it is understood to be sound at frequencies below 20 Hz to cover frequencies corresponding to rotor rpm times the number of blades on the wind turbine.

It is a general understanding that infrasound is present in the sound spectrum from a modern wind turbine with the rotor upwind of the tower. However, it is well below the hearing threshold. Modern wind turbines are designed to reduce the forces related to the blade passage of the tower which was the cause of the infrasound generated by the early megawatt prototype downwind wind turbines from the 1980 to 1990.

Measurements show that infrasound from current wind turbine designs is well below the hearing threshold even though it is measurable.

Significant research reviews have been carried out in Germany, Canada, Finland and Holland, all confirming that there is no evidence that sound levels attributable to wind turbines are loud enough to have any measurable effect.

See the numbered Bibliography for more information.

Annex C
(informative)

Low frequency sound evaluation

C.1 Outline

Low frequency sound is typically defined to be in the range from 10 Hz to 200 Hz. However, this is not a standardised definition and can vary in different countries. Low frequency sound is most audible indoors as buildings work as a low-pass filter, filtering out the higher frequencies.

Many anthropogenic sound sources such as road traffic, aircraft, heavy industrial machinery (including wind turbines) and even air conditioning emit sound at low frequencies. Examples of natural sources of low frequency sound are waves on the sea, rivers, waterfalls and the wind in the surroundings.

Local regulations can give guidance for the determination of low frequency sound levels and appropriate limits for low frequency sound.

Measurement of low frequency sound levels from wind turbines is feasible close to the wind turbine. There is general agreement, however, that direct measurement of low frequency sound at a distance from a wind turbine is difficult. Furthermore, the measurement of low frequency sound indoors can be complicated by room specific conditions such as room dimensions and the sound absorption of the surfaces in the room. This can require multiple microphone positions to be monitored simultaneously. This is a rather intrusive measurement in an inhabited residence. Wind turbine sound measurements shall be taken over long periods as outlined in Clause 11. It is impractical to isolate non-wind turbine low frequency sound over long measurement periods inside a residence. For these reasons a standardised calculation approach is by far the most reliable and reproducible approach.

The purpose of Annex C is to describe the preferred methodology for determination of the low frequency sound levels originating from wind turbines. The method can be used at any wind speed, where the sound power level(s) of the wind turbine(s) has(have) been determined.

The sound power levels in 1/3-octave bands are being used in a sound prediction taking into account façade sound insulation values typical for the country and style of house for the given task, to arrive at an indoor low frequency sound pressure level. (See Clause C.2 for more details).

C.2 Standardised prediction approach

The prediction is made in 1/3-octave bands. Input to the model is sound power emissions determined according to IEC 61400-11. The low frequency transmission loss calculation is carried out using the Nord2000 approach to determine the immission level. The immission level can be calculated as an unweighted, A-weighted, internal or external sound pressure level depending on local regulation. The calculation can also be completed using specific meteorological and ground absorption factors.

$$L_{\text{p,LF}} = L_{\text{W,LF}} - 10\log\left(l^2 + h^2\right) - 11\text{dB} + \Delta L_{\text{g,LF}} - \Delta L_a - \Delta L_\sigma \tag{C.1}$$

where

$L_{W,\text{LF}}$ is the emitted sound power level for the 1/3-octave band frequency, measured following IEC 61400-11

l is the distance between the wind turbine tower center line and the receptor position

h is the wind turbine hub height

11 dB is the distance correction term: 10log(4 π)

$\Delta L_{g,LF}$ is the low frequency ground correction. Tabulated values that cover ground type (impedance class) D can be used (see Table C.1)

ΔL_a is the air absorption = (α * √(l2 + h2)) absorption coefficients (see Table C.2)

ΔL_σ is the façade sound insulation (standardised values for groups of houses, typically part of local regulation)

Table C.1 – Impedance class descriptions

Impedance class	Representative flow resistivity σ(kPasm^{-2})	Range of Nordtest flow resistivity classes	Description
A	12,5	10, 15	Very soft (snow, moss like)
B	32	25, 40	Soft forest floor (short dense heatherlike or thick moss)
C	80	63, 100	Uncompacted loose ground (turf, grass, loose soil)
D	200	160, 250	Normal uncompacted ground (forest floor, pasture field)
E	500	400, 630	Compacted field and gravel (compacted lawns, park area)
F	2 000	2 000	Compacted dense ground (gravel road, parking lot, ISO 10844)
G	20 000	-	Hard surface (most normal asphalt, concrete)
H	200 000	-	Very hard and dense surfaces (dense asphalt, concrete, water)

This equation works independently of wind speed, however a wind speed range corresponding to the required wind speed range in IEC 61400-11 is recommended. Where no local regulation exists, the conditions in Table C.2 corresponding to impedance class D are recommended.

Table C.2 – Equation coefficients for a rural setting at 70 % humidity and 10 °C

1/3-octave band centre frequency [Hz]	10	12,5	16	20	25	31,5	40	50	63	80	100	125	160	200
$\Delta L_{g,LF}$ – on shore wind turbines	6,0	6,0	5,8	5,6	5,4	5,2	5,0	4,7	4,3	3,7	3,0	1,8	0,0	0,0
α [dB/km]	0,0	0,0	0,0	0,0	0,02	0,03	0,05	0,07	0,11	0,17	0,26	0,41	0,59	0,80
ΔL_σ (local regulation)	X,X	X,X	X,X	X,X	X,X	X,X	X,X	X,X	X,X	X,X	X,X	X,X	X,X	X,X

The air absorption coefficient is calculated according to ISO 9613-1. Local conditions can apply.

The façade insulation values are usually part of the local regulation and depend on local construction of houses and knowledge of sound insulation values of building material. If in doubt, values should be agreed between parties. If no data are available the façade insulation can be determined according to the principles of ISO 16283-3. The standard gives a lower frequency of 50 Hz, but with sufficient loudspeaker signal the method is expected to be valid for the entire frequency range in question. It is recommended to use generalised values for certain architectural style and not specific data for individual houses.

Table C.3 – Examples of façade insulation values ΔL_σ

1/3-octave band centre frequency [Hz]	10	12,5	16	20	25	31,5	40	50	63	80	100	125	160	200
Denmark brick or similar	4,9	5,9	4,6	6,6	8,4	10,8	11,4	13,0	16,6	19,7	21,2	20,2	21,2	21,0
Denmark lightweight	6,8	3,9	0,4	-0,2	4,8	6,2	8,4	10,5	11,9	11,9	16	17,5	17,9	17,0
ΔL_σ (local regulation)	X,X	X,X	X,X	X,X	X,X	X,X	X,X	X,X	X,X	X,X	X,X	X,X	X,X	X,X

The values in Table C.3 are given as 67 % confidence level for typical northern European house façades.

C.3 Data reduction

Calculations at a single wind speed, for a defined range of wind speeds or the maximum sound emission case can be done. Local regulations with regard to calculations can apply. Predictions can be tabulated in individual 1/3-octave bands. The results of the prediction can be compared to the regulations directly for each wind speed/situation or as equivalent sound pressure level based on the sum of a set of 1/3-octave bands. In this case the equivalent level has to be calculated before comparing with regulations.

C.4 Uncertainty

The principles from 9.2 on uncertainty can be applied to each 1/3-octave band individually.

C.5 Reporting

Results are to be reported as tabulated values. Regulatory requirements can apply. An example is given in Table C.4:

Table C.4 – Low frequency measurements reporting table

1/3-octave band center frequency [Hz]	10	12,5	16	20	25	31,5	40	50	63	80	100	125	160	200	Equivalent level
$L_{w,LF}$															
A-weighting (if used)	-70,4	-63,4	-56,7	-50,5	-44,7	-39,4	-34,6	-30,2	-26,2	-22,5	-19,1	-16,1	-13,4	-10,9	
+ 10log (l^2 +h^2)															
- 11 dB	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	
+ ΔL_{gLF}															
- ΔL_a															
$L_{A,LF}$ outdoor*															
- ΔL_σ															
$L_{pA,LF}$ indoor[a]															
Criterion curve															
Criterion fulfilled															

[a] Or $L_{p,LF}$ (unweighted) as required.

The criterion to fulfil can be either a summed 1/3-octave band LF level (energy averaging to be applied) or a criterion curve to fulfil at each 1/3-octave band.

L_A is the energetic sum of the contributions from the relevant wind turbines in the wind farm.

C.6 Examples of sound criteria in Scandinavian countries

C.6.1 Denmark

$L_{A,LF}$ ≤ 20 dB(A) determined as the equivalent A-weighted sound level based on 1/3-octave bands from 10 Hz to 160 Hz at 6 m/s and 8 m/s standardised wind speed at 10 m reference height.

C.6.2 Sweden

The following values (see Table C.5) are used in Sweden, which go back to the report [27].

Table C.5 – Z-weighted sound levels in individual 1/3-octave bands from 31,5 Hz to 200 Hz

1/3-octave band frequency [Hz]	31,5	40	50	63	80	100	125	160	200
L_{pZ} [dB]	56	49	43	42	40	38	36	34	32

Annex D
(informative)

Examples for test plan and other considerations

D.1 General

Annex D gives examples of test cases and other situations, which the user can face when planning and executing a test according to this document. This includes typical examples, but also untypical cases which can require special treatment.

These examples are not intended to be followed in detail. They shall guide the user how to ask themselves the right questions, consider options and to derive the best decisions for their individual test case.

D.2 Understanding the test scope and setting up a test plan – Example 1

Compliance of the wind farm sound contribution with a fixed sound pressure level limit shall be shown, as well as non-occurrence of tonal audibility above a certain threshold, while masking of tonal noise by background sound created near the receptor locations (trees around the house) shall be acceptable. The wind turbines comprising the wind farm are known to have a potential risk of tonal sound emission around 8 m/s at hub height, preferably in cross-wind conditions. The maximum sound power levels of the aforesaid wind turbine type are in the range of 6 m/s to 12 m/s at hub height.

Proposed measurement setup: Measurements suitable for the determination of sound pressure levels shall be executed on a proxy location to the receptor under investigation (see Annex I on proxy location) in free field at least 100 m distant from any trees. Alternatively: Microphone setup on a façade to further increase signal-to-noise ratio to a sufficient level. This measurement shall be a long-term measurement to cover a wind speed range of at least 6 m/s to 12 m/s at hub height, filtered for down-wind conditions. It shall cover the required situations defined in the test plan. In order to distinguish between wind farm sound contribution and background sound levels, on/off testing is required, where testing with the wind farm being offline shall provide stable and reliable results.

A second sound measurement shall be executed as a short-term measurement in order to investigate tonal audibility, covering 7 m/s to 9 m/s at hub height in cross-wind conditions. The microphone shall be located at the receptor location (the exact position shall be representative for typical or worst-case listener positions). This measurement is best executed during the autumn or winter period, while the trees have no leaves, to represent worst-case (i.e. least) masking conditions for tonal sound from the wind farm. No on-off testing is required except if a potential tone shall be proven to not be originating from the wind farm.

D.3 Understanding the test scope and setting up a test plan – Example 2

A flat noise limit of 40 dB(A) applies for a receptor location. Sound predictions indicate that this noise limit might be exceeded under certain conditions. On the opposite side of the wind turbine relative to the receptor location, a busy road is present, from which significant sound levels above 40 dB(A) are expected. Thus, the wind turbine sound might be masked by the traffic noise at all times. The wind turbine type is known to emit highest sound power levels in the wind speed range of 9 m/s to 12 m/s at hub height.

Proposed measurement setup: Measurements suitable for the determination of sound pressure levels shall be executed as short-term measurements. The microphone shall be set up in front of the façade of the house facing toward the wind turbine (distance and microphone height to be determined). In this position, the highest expected contribution from the wind turbine and the lowest expected level of traffic noise due to shielding by the house itself will occur. The measurement shall be conducted when the wind speed cover the wind speed range of 8 m/s to 13 m/s at hub height under downwind conditions for the receptor (relative to the wind turbine to provide optimal conditions of nonmasking the wind farm sound). To minimize the masking of wind farm sound, the measurement should be attempted during a period such as on a night between Saturday and Sunday in a period between 01:00 and 04:00 in the morning, which is the period assumed to show the lowest traffic rates. On-off measurements can require to be executed in order to determine the contribution from the traffic noise to the overall sound level. If the difference between total sound and traffic noise is more than 3 dB, a background sound correction can be carried out (see 11.7). If the difference is less than 3 dB, the wind farm sound contributes less to the overall sound level than the traffic noise and is thus 'masked'. As sound propagation conditions might differ in their influence on low-elevation sound from traffic versus high-elevation sound from wind farms, two measurements shall be executed if masking is found to occur: one under favourable sound propagation conditions (temperature inversion during clear skies), the other one under adverse propagation conditions (instable atmospheric conditions with ≥ 7/8 cloud cover). Both tests shall show sufficient masking of the wind farm sound by traffic sound if masking is the final conclusion.

D.4 Advantages and disadvantages of different measurement methodologies for L_p

D.4.1 Long term measurements of wind turbine operation without shut down

This method is outlined in 11.6.1. It involves conducting measurements with the wind farm in operation, during times of low background sound level (such as high shear events with low ground level wind speed). No background sound measurements are conducted and a conservative assessment can be made of wind farm sound level.

When considering this method it is noteworthy that:

- it only provides a meaningful result, when the measured overall sound level is below a given limit value, i.e. when compliance with the limit value is proven. If the overall sound level is above a given limit, no statement of compliance or incompliance with the limit value can be given;
- no distinction between wind farm sound and background sound contribution can be made;
- this measurement provides results which are only representative for the environmental conditions, especially meteorological ones, which were prevailing during the test. There is no direct indication of results under different environmental conditions.

D.4.2 Short term measurements including periods of wind turbine operation and shut down

The short term method is outlined in 11.6.2. It involves short term measurements, sometimes attended, during the representative conditions of interest where measurements are conducted with the wind farm operating or stopped within a short time, and the results are used to arrive at a background corrected sound level from the wind farm.

When considering this method, it is noteworthy that:

- it provides information on both total sound and background sound, allowing the determination of the pure wind farm sound contribution (provided signal to noise (SNR) ratio is good enough);
- since measurements are done under well defined, sufficiently constant environmental conditions, few data points will provide enough statistical safety, which keeps the effort of the measurement low;

- this measurement provides results which are only representative for the environmental conditions, especially meteorological ones, which were prevailing during the test. There is no direct indication of results under different environmental conditions;
- the wind speed range covered during short term measurements is typically smaller than the range covered during long term measurements;
- it can be difficult to find on-off periods long enough under constant environmental conditions as laid out above;
- it requires to stop the wind farm for the time of off-testing, which will lead to financial losses.

D.4.3 Long term measurements including periods of wind turbine operation and shut down

Long term measurements typically involve unattended measurement stations with continuous measurements carried out over longer periods (several days, weeks or months). The measurements are taken during the campaign will include both ON and OFF conditions of the wind farm. The measurements are then reduced to remove transient contamination and binned by wind speed and wind direction. The appropriate background corrections are then carried out within the same environmental conditions, and a wind farm sound level contribution is determined.

When considering the long term measurement method, the following is noteworthy:

- It provides information on both total sound and background sound, allowing the determination of the pure wind farm sound contribution (provided signal-to-noise ratio is good enough), similar to short term measurements including periods of wind turbine operation and shut down.
- Since measurements are conducted over a longer duration during which wider range of environmental and operation conditions will be encountered, more conclusions can be drawn out of the data.
- The overall duration, effort and cost of long term operation cycling is generally higher than for short term operation cycling.
- If multiple environmental or operational conditions have to be addressed, more data points are required to reach enough statistical safety of the results and conclusions.
- Cleaning measurement data from intermittent extraneous sound can be more difficult than for attended short term measurements.
- It requires to stop the wind farm for the time of off-testing, which could lead to larger financial losses than short term operation cycling.

Annex E
(informative)

Objective method for assessing the audibility of tones in sound – Survey method

It is understood that tones cannot be identified by the evaluation of octave bands. In addition, the use of 1/3-octave band-based tonality methods is not encouraged. One of the shortcomings of 1/3-octave band-based tonality analysis is the inability to identify tones with frequencies near or on the boundary of the 1/3-octave band. For a more detailed discussion of 1/3-octave band tonal analysis see Søndergaard and Bastasch [9] who reviewed ISO 1996-2, ANSI/ASA S12.9-2005/Part 4 and ANSI/ASA S12.9-2013/Part 3.

ISO 1996-2, ANSI/ASA S12.9-2005/Part 4 and ANSI/ASA S12.9-2013/Part 3 methods evaluate the prominence of a 1/3-octave band tonal analysis by comparing the magnitude of the 1/3-octave bands of interest with those of the immediately adjacent bands. Each identifies the same frequency dependent choices for constant level differences:

+ 15 dB in the low-frequency range (25 Hz to 125 Hz),

+ 8 dB in middle-frequency range (160 Hz to 400 Hz),

+ 5 dB in high-frequency range (500 Hz to 10 000 Hz).

Whilst not explicitly stated, it is expected that this comparison is carried out on unweighted or linear spectra. ISO 1996-2 and ANSI/ASA S12.9-2005/Part 4 are interpreted as requiring the band of interest to exceed both adjacent side bands by the criteria. ANSI/ASA S12.9-2013/Part 3 bases the comparison on the difference between the band of interest and the arithmetic average of the adjacent side bands. Søndergaard and Bastasch [9] identified that the arithmetic averaging of the side band method of ANSI/ASA S12.9-2013/Part 3 yielded better tonal detection than ISO 1996-2 and ANSI/ASA S12.9-2005/Part 4, but all methods failed when tones were near the boundary of the band.

NOTE The implementation of the arithmetic averaging method is better described in the regulatory text than in the standards and is provided below from the US State of Illinois [20] as an example:

"...sound, having a one-third octave band sound pressure level which, when measured in a one-third octave band at the preferred frequencies, exceeds the arithmetic average of the sound pressure levels of the two adjacent one-third octave bands on either side of such one-third octave band by:

1) *5 dB for such one-third octave band with a center frequency from 500 Hertz to 10,000 Hertz, inclusive. Provided: such one-third octave band sound pressure level exceeds the sound pressure level of each adjacent one-third octave band, or;*
2) *8 dB for such one-third octave band with a center frequency from 160 Hertz to 400 Hertz, inclusive. Provided: such one-third octave band sound pressure level exceeds the sound pressure level of each adjacent one-third octave band, or;*
3) *15 dB for such one-third octave band with a center frequency from 25 Hertz to 125 Hertz, inclusive. Provided: such one-third octave band sound pressure level exceeds the sound pressure level of each adjacent one-third octave band."*

Annex F
(informative)

Data exclusion tools

F.1 General

When considering the quality of the measured data there will be disturbances that have to be excluded from the dataset to give a correct representation of the sound from the source. It is necessary that these disturbances are described and that it is explained why these data should be excluded. This applies to measurements of all sound characteristics. If background sound correction is applied it is important that data exclusion in background sound measurements is made from the same principles as for total sound measurements.

Examples of different types of exclusions that can be relevant are:

1) Time based
   a) Animal or insect based examples are
      i) dawn chorus (exclude period)
      ii) crickets (low pass filtering or exclude period)
      iii) frogs and toads
   b) Intermittent or timed activity or machinery examples are
      i) boiler
      ii) milking time on a farm
      iii) closing time of night-time establishments
      iv) rush hour traffic noise
2) Meteorology based examples are
   a) further rainfall exclusions – watercourse flow levels
   b) extreme low temperatures – reduced activity/changed propagation conditions
   c) temperature inversions
3) Irregular sound sources examples are
   a) lawn mowing
   b) animal near microphone
   c) idling vehicle

F.2 General data exclusion tools and methods

For identifying periods or data that should be excluded the following tools or methods could be helpful.

1) Time history chart: Time history plots of noise data, synchronized with wind turbine operations, wind speed data, etc., illustrate when the measured noise level is reflective of turbine noise only and when it is reflective of significant nonturbine contributions. For example, turbine-only noise is generally steady under full operating conditions, whereas noise levels tend to fluctuate to a much greater degree when ground winds are gusty. Individual vehicle pass-bys and other erratic “events” will be obvious.
   a) L_p, windspeed, wind direction, rainfall, wind turbine operation
   b) 10 min to 72 h

2) Waterfall plot, spectrograms and other frequency analysis. The spectral composition of wind turbine-only noise is relatively consistent at a given location under consistent wind speeds and directions. The spectral shape of turbine-only noise can be determined from periods of high shear (extremely low ground wind). Measurements with erratic spectral shapes, or spectral shapes that deviate from the turbine-only spectral shape, indicate contributions from nonturbine noise sources. This is particularly useful when attempting to determine influences from sources of continuous background noise, such as a constant wind or distant highway.

   a) Frequency versus time (power or RPM) with level in colour

   b) 1 s to 1 h

3) L_{Axx} versus L_{Aeq} See H.2.1.

4) Simultaneous multi-measurement comparison at different locations. Comparing turbine-only levels at two or more measurement locations near a wind project to determine if a phenomenon is specific to one turbine or location or a sitewide issue. Using a “control” location that is relatively close to another measurement but much closer to the nearest turbine(s).

5) Meteorological versus L_{p} scatter plot

   a) Windspeed, wind direction, temperature, humidity, etc.

   b) Shows trends and outliers (e.g. icing)

6) AM specific data exclusion tools

   a) Modulation frequency versus wind speed/wind direction with wind turbine blade passage superimposed

   b) Comparing frequency bands

   c) Comparing modulation frequency statistics

7) Tonality specific data exclusion tools

   a) Tone frequency versus wind speed chart to show trends and outliers

   b) Comparing tone frequency statistics within 1 min period (3 s values)

   c) Check for tones in background sound

Annex G
(informative)

Amplitude modulation adaptions

G.1 General

There are some situations where analysed turbine sound immissions are not well characterised by the standard method outlined in Clause 13. At the time of writing, two key situations are the most common in smaller scale turbines. These are:

- the turbine rotor having a rotor rpm and configuration resulting in a modulation frequency above 1,6 Hz (e.g. a three-bladed turbine with a rotor rpm greater than 32);
- the modulating sound occurring at frequencies above 800 Hz (and thus outside the three standard frequency bands).

The latter situation usually occurs due to a combination of smaller, faster rotors producing sound with a larger high frequency content, and the receptor locations being closer to the turbines, and thus a lesser degree of high frequency attenuation.

Annex G briefly details ways in which the method in Clause 13 can be varied to account for these situations. Note that these are only suggestions, and these alterations are not yet widely used and therefore should be treated with some caution.

It should be noted that fluctuation strength is highest (resulting in the worst-case situation perceptually) where a ~1 kHz signal is being modulated at ~4 Hz. Where amplitude modulation occurs close to these parameters, it can be that the metric and any penalties based on the standard method will diverge from the dose response testing upon which they are based.

G.2 Faster rotor speeds

Where a rotor rpm results in a modulation frequency above 1,6 Hz, it is no longer possible to include the third harmonic's energy in the AM calculations. However, it is suggested that, although this will result in a slight underestimation of the modulation energy, that in lieu of an alternative adaption to the method, the analysis should be carried out despite this limitation in the inclusion of harmonic energy, and acknowledged in the presentation of the results.

It is recommended that, where this adaption is used, the contribution of the first harmonic should be investigated as an indicator as to whether there is likely to be significant energy not accounted for in the third harmonic. Usually the second harmonic is more dominant and a lack of significant energy in the second harmonic would imply that the third harmonic would be insignificant, although this is not always the case. This should be commented on in the presentation of the results. If there is concern over the significance of the third harmonic's energy, this should be investigated further.

G.3 Higher frequency bands

Where it is suspected or expected that frequencies above 800 Hz are being modulated (such as for smaller turbines) additional frequency bands should be investigated above the 50 Hz to 200 Hz, 100 Hz to 400 Hz and 200 Hz to 800 Hz bands detailed in 13.6.2.1.1. These bands are suggested to include the seven 1/3-octave bands with centres of:

- Band 4: 400 Hz to 1 600 Hz
- Band 5: 800 Hz to 3 200 Hz
- Band 6: 1 600 Hz to 6 400 Hz

These bands should be calculated in addition to the three standard bands, and the worst-case bands for each bin used, as per Clause 13.

Note that the reason for band limiting the data in the first place is to avoid other sound sources from triggering false-positives, and as such, including these higher bands, although necessary in some cases, also requires careful considering and justification. It is crucial to listen to periods of high modulation using these bands as there is an increased likelihood of other sound sources triggering AM results. Although this should be done for the standard method, additional diligence is required when using the three higher bands.