



BSI Standards Publication

Wind energy generation systems

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

National foreword

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A list of organizations represented on this committee can be obtained on request to its committee manager.

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TECHNICAL SPECIFICATION



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

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

WIND ENERGY GENERATION SYSTEMS –

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

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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

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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 μ Pa.**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 adaptations (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 $\pm 0,5$ 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 $\pm 45^\circ$).

- 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 $\pm 0,05$ 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 to 13 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 $\pm 40\%$ 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 choose 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).