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Wind turbine generator systems –
Part 11: Acoustic noise measurement techniques

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WIND TURBINE GENERATOR SYSTEMS –

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FOREWORD

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International Standard IEC 61400-11 has been prepared by IEC technical committee 88: Wind turbines.

This consolidated version of IEC 61400-11 consists of the second edition (2002) [documents 88/166/FDIS and 88/171/RVD] and its amendment 1 (2006) [documents 88/260/FDIS and 88/264/RVD].

The technical content is therefore identical to the base edition and its amendment and has been prepared for user convenience.

It bears the edition number 2.1.

A vertical line in the margin shows where the base publication has been modified by amendment 1.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of the base publication and its amendments will remain unchanged until the maintenance result date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

INTRODUCTION

The purpose of this part of IEC 61400 is to provide a uniform methodology that will ensure consistency and accuracy in the measurement and analysis of acoustical emissions by wind turbine generator systems. The standard has been prepared with the anticipation that it would be applied by:

- the wind turbine manufacturer striving to meet well defined acoustic emission performance requirements and/or a possible declaration system;
- the wind turbine purchaser in specifying such performance requirements;
- the wind turbine operator who may be required to verify that stated, or required, acoustic performance specifications are met for new or refurbished units;
- the wind turbine planner or regulator who must be able to accurately and fairly define acoustical emission characteristics of a wind turbine in response to environmental regulations or permit requirements for new or modified installations.

This standard provides guidance in the measurement, analysis and reporting of complex acoustic emissions from wind turbine generator systems. The standard will benefit those parties involved in the manufacture, installation, planning and permitting, operation, utilization, and regulation of wind turbines. The measurement and analysis techniques recommended in this document should be applied by all parties to insure that continuing development and operation of wind turbines is carried out in an atmosphere of consistent and accurate communication relative to environmental concerns. This standard presents measurement and reporting procedures expected to provide accurate results that can be replicated by others.

WIND TURBINE GENERATOR SYSTEMS –

Part 11: Acoustic noise measurement techniques

1 Scope

This part of IEC 61400 presents measurement procedures that enable noise emissions of a wind turbine to be characterised. This involves using measurement methods appropriate to noise emission assessment at locations close to the machine, in order to avoid errors due to sound propagation, but far enough away to allow for the finite source size. The procedures described are different in some respects from those that would be adopted for noise assessment in community noise studies. They are intended to facilitate characterisation of wind turbine noise with respect to a range of wind speeds and directions. Standardisation of measurement procedures will also facilitate comparisons between different wind turbines.

The procedures present methodologies that will enable the noise emissions of a single wind turbine to be characterised in a consistent and accurate manner. These procedures include the following:

- location of acoustic measurement positions;
- 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 emission parameters, and associated descriptors which are used for making environmental assessments.

The standard is not restricted to wind turbines of a particular size or type. The procedures described in this standard allow for the thorough description of the noise emission from a wind turbine. If, in some cases, less comprehensive measurements are needed, such measurements are made according to the relevant parts of this standard.

2 Normative references

The following referenced documents are indispensable for the application 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 60386:1972, *Method of measurement of speed fluctuations in sound recording and reproducing equipment*

IEC 60651:1979, *Sound level meters*

IEC 60688:1992, *Electrical measuring transducers for converting a.c. electrical quantities to analogue or digital signals*

IEC 60804:2000, *Integrating-averaging sound level meters*

IEC 60942:1997, *Electroacoustics – Sound calibrators*

IEC 61260:1995, *Electroacoustics – Octave-band and fractional-octave-band filters*

IEC 61400-12:1998, *Wind turbine generator systems – Part 12: Wind turbine power performance testing*

3 Definitions

For the purposes of this standard, the following definitions apply:

3.1
apparent sound power level
L_{WA} (in dB re. 1 pW)
the 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 each wind speed integer from 6 to 10 m/s

3.2
audibility criterion
L_a (in dB re. 20 µPa)
a frequency dependent criterion curve determined from listening tests, and reflecting the subjective response of a 'typical' listener to tones of different frequencies

3.3
A-weighted or C-weighted sound pressure levels
L_A or L_C, respectively (in dB re. 20 µPa)
sound pressure levels measured with the A or C frequency weighting networks specified in IEC 60651

3.4
directivity
Δ_i (in dB)
the difference between the A-weighted sound pressure levels measured at measurement positions 2, 3, and 4 and those measured at the reference position 1 from the turbine corrected to the same distance from the wind turbine rotor centre

3.5
inclination angle
ϕ (in °)
the angle between the plane of the microphone board and a line from the microphone to the rotor centre

3.6
reference distance
R_0 (in m)
the nominal horizontal distance from the centre of the base of the wind turbine to each of the prescribed microphone positions

3.7
reference height
z_{ref} (in m)
a height of 10 m used for converting wind speed to reference conditions

3.8
reference roughness length
z_{0ref} (in m)
a roughness length of 0,05 m used for converting wind speed to reference conditions

3.9
sound pressure level
L_p (in dB re. 20 µPa)
10 times the $\log_{10}$ of the ratio of the mean-square sound pressure to the square of the reference sound pressure of 20 µPa

3.10
standardized wind speed
V_s (in ms^{-1})
wind speed converted to reference conditions (height 10 m and roughness length 0,05 m) using a logarithmic profile

3.11
tonal audibility $\Delta L_{a,k}$ (in dB)
The difference between the tonality and the audibility criterion at integer wind speeds k = 6, 7, 8, 9, 10

3.12
tonality ΔL_k (in dB)
the difference between the tone level and the level of the masking noise in the critical band around the tone at integer wind speeds k = 6, 7, 8, 9, 10

4 Symbols and units

D	rotor diameter (horizontal axis turbine) or equatorial diameter (vertical axis turbine)	(m)
H	height of rotor centre (horizontal axis turbine) or height of rotor equatorial plane (vertical axis turbine) above local ground near the wind turbine	(m)
L_A or L_C	A or C-weighted sound pressure level	(dB)
$L_{Aeq,k}$	equivalent continuous A-weighted sound pressure level at each integer wind speed, where k = 6, 7, 8, 9, 10	(dB)
$L_{Aeq,c,k}$	equivalent continuous A-weighted sound pressure level corrected for background noise at each integer wind speed and corrected to reference conditions, where k = 6, 7, 8, 9, 10	(dB)
$L_{Aeq,i}$	equivalent continuous A-weighted sound pressure level in position 'i' corrected for background noise where i = 1, 2, 3, or 4	(dB)
L_n	equivalent continuous sound pressure level of the background noise	(dB)
$L_{pn,j,k}$	sound pressure level of masking noise within a critical band in the 'j^{th}' spectra at the 'k^{th}' wind speed, where j = 1 to 12 and k = 6, 7, 8, 9, 10	(dB)
$L_{pn,avg,j,k}$	average of analysis bandwidth sound pressure levels of masking in the 'j^{th}' spectra at the 'k^{th}' wind speed, where j = 1 to 12 and k = 6, 7, 8, 9, 10	(dB)
$L_{pt,j,k}$	sound pressure level of the tone or tones in the 'j^{th}' spectra at the 'k^{th}' wind speed, where j = 1 to 12 and k = 6, 7, 8, 9, 10	(dB)
L_s	equivalent continuous sound pressure level of only wind turbine noise	(dB)
L_{s+n}	equivalent continuous sound pressure level of combined wind turbine and background noise	(dB)
$L_{WA,k}$	apparent sound power level, where k = 6, 7, 8, 9, 10	(dB)
P_m	measured electric power	(W)
P_n	normalised electric power	(W)

R_i	slant distance, from rotor centre to actual measurement position ‘i’, where i = 1, 2, 3, or 4	(m)
R_0	reference distance	(m)
S_0	reference area, S_0 = 1 m^2	(m^2)
T_C	air temperature	(C)
T_K	air temperature	(K)
U_A, U_B	uncertainty components	(dB)
V_H	wind speed at hub height, H	(m/s)
V_D	derived wind speed from power curve	(m/s)
V_n	wind speed measured by the nacelle anemometer	(m/s)
V_z	wind speed at height, z	(m/s)
V_s	standardized wind speed	(m/s)
f	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)
z_{ref}	reference height for wind speed, 10 m	(m)
β	angle used to define allowable area for anemometer mast location	(°)
κ	the ratio of standardised wind speed and measured wind speed	
Δ_i	directivity at ‘i^{th}’ position, where i = 2, 3, or 4	(dB)
$\Delta_{Ltn,j,k}$	tonality of the ‘j^{th}’ spectra at ‘k^{th}’ wind speed, where j = 1 to 12 and k = 6, 7, 8, 9, 10	(dB)
ϕ	inclination angle	(°)

5 Outline of method

This Part of IEC 61400 defines the procedures to be used in the measurement, analysis and reporting of acoustic emissions of a wind turbine. Instrumentation and calibration requirements are specified to ensure accuracy and consistency of acoustic and non-acoustic measurements. Non-acoustic measurements required defining the atmospheric conditions relevant to determining the acoustic emissions are also specified. All parameters to be measured and reported are identified, as are the data reduction methods required for obtaining these parameters.

Application of the method described in this International Standard provides the apparent A-weighted sound power levels, spectra, and tonality at integer wind speeds from 6 to 10 m/s of an individual wind turbine. Optionally, directivity may also be determined.

The measurements are made at locations close to the turbine in order to minimise the influence of terrain effects, atmospheric conditions or wind-induced noise. To account for the size of the wind turbine under test, a reference distance R_0 based on the wind turbine dimensions is used.

Measurements are taken with a microphone positioned on a board placed on the ground to reduce the wind noise generated at the microphone and to minimise the influence of different ground types.

Measurements of sound pressure levels and wind speeds are made simultaneously over short periods of time and over a wide range of wind speeds. The measured wind speeds are converted to corresponding wind speeds at a reference height of 10 m and a reference roughness length of 0,05 m. The sound levels at standardized wind speeds of 6, 7, 8, 9, and 10 m/s are determined and used for calculating the apparent A-weighted sound power levels.

If this part of IEC 61400 is used for verification that actual noise emission is in accordance with a reference/declared noise level, the verification measurement shall be made in accordance with the present standard for a wind speed range given by:

- Annual average wind speed at 10 m height onsite ±1 m/s as a minimum. As a minimum, three integer wind speed values and 8 m/s shall be reported (i.e. site average = 4,8 m/s, use 4, 5, 6, and 8 m/s).
- If the declaration measurements indicate that audible tones are present at other wind speeds, these wind speeds shall be included as well.

Where local codes or contracts between parties involved (i.e. manufacturers, developers, owners) require measurements at a different wind speed or wind speed range, this part of IEC 61400 may be applied at those wind speeds.

The directivity is determined by comparing the A-weighted sound pressure levels at three additional positions around the turbine with those measured at the reference position.

Informative annexes are included that cover

- other possible characteristics of wind turbine noise emission and their quantification (Annex A);
- criteria for recording/playback equipment (Annex B);
- assessment of turbulence intensity (Annex C);
- assessment of measurement uncertainty (Annex D).

6 Instrumentation

6.1 Acoustic instruments

The following equipment is necessary to perform the acoustic measurements as set forth in this standard.

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

The equipment shall meet the requirements of a type 1 sound level meter according to IEC 60804. The diameter of the microphone shall be no greater than 13 mm.

6.1.2 Equipment for the determination of one-third octave band spectra

In addition to the requirements given for type 1 sound level meters, the equipment shall have a constant frequency response over at least the 45 Hz to 11 200 Hz frequency range. The filters shall meet the requirements of IEC 61260 for Class 1 filters.

The equivalent continuous sound pressure levels in one-third octave bands shall be determined simultaneously with centre frequencies from 50 Hz to 10 kHz. It may be relevant to measure the low-frequency noise emission of a wind turbine. In such cases, a wider frequency range is necessary as discussed in Annex A.

6.1.3 Equipment for the determination of narrow band spectra

The equipment shall fulfil the relevant requirements for IEC 60651 type 1 instrumentation in the 20 Hz to 11 200 Hz frequency range.

6.1.4 Microphone with measurement board and windscreen

The microphone shall be mounted at the centre on a flat hard board with the diaphragm of the microphone in a plane normal to the board and with the axis of the microphone pointing towards the wind turbine, as in Figures 1 and 2. The board shall be circular with a diameter of at least 1,0 m and made from material that is acoustically hard, such as plywood or hard chip-board with a thickness of at least 12,0 mm or metal with a thickness of at least 2,5 mm. A larger board is recommended especially for soft ground. In the exceptional case that the board is split (i.e. not in one piece) there are considerations; the pieces shall be level within the same plane, the gap less than 1 mm, and the split must be off the centre line and parallel with the microphone axis as shown in Figure 1a).

The windscreen to be used with the ground-mounted microphone shall consist of a primary and, where necessary, a secondary windscreen. The primary windscreen shall consist of one half of an open cell foam sphere with a diameter of approximately 90 mm, which is centred around the diaphragm of the microphone, as in Figure 2.

The secondary windscreen may be used when it is necessary to obtain an adequate signal-to-noise ratio at low frequencies in high winds.

For example, it could consist of a wire frame of approximate hemispherical shape, at least 450 mm in diameter, which is covered with a 13 mm to 25 mm layer of open cell foam with a porosity of 4 to 8 pores per 10 mm. This secondary hemispherical windscreen shall be placed symmetrically over the smaller primary windscreen.

If the secondary windscreen is used, the influence of the secondary windscreen on the frequency response must be documented and corrected for.

6.1.5 Acoustical calibrator

The complete sound measurement system, including any recording, data logging or computing systems, shall be calibrated immediately before and after the measurement session at one or more frequencies using an acoustical calibrator on the microphone. The calibrator shall fulfil the requirements of IEC 60942 class 1, and shall be used within its specified environmental conditions.

6.1.6 Data recording/playback systems

A data recording/playback system is a required part of the measurement instrumentation, and the entire chain of measurement instruments shall fulfil the relevant requirements of IEC 60651, for type 1 instrumentation. Examples are given in Annex B.

6.2 Non-acoustic Instruments

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

6.2.1 Anemometers

The anemometer and its signal processing equipment shall have a maximum deviation from the calibration value of ±0,2 m/s in the wind speed range from 4 m/s to 12 m/s. It shall be capable of measuring the average wind speed over time intervals synchronized with the acoustic measurements.

Because the nacelle anemometer is *in situ* calibrated during measurement, the demand for calibration does not apply to the nacelle anemometer. The measurements from the nacelle anemometer may be supplied from the wind turbine control system. The nacelle anemometer shall not be used for background noise measurements.

6.2.2 Electric power transducer

The electric power transducer, including current and voltage transformers, shall meet the accuracy requirements of IEC 60688 Class 1.

6.2.3 Wind direction transducer

The wind direction transducer shall be accurate to within ±6°.

6.2.4 Other instrumentation

A camera and instruments to measure distance are required. The temperature shall be measured with an accuracy of ±1°C. The atmospheric pressure shall be measured with an accuracy of ±1 kPa.

6.3 Traceable calibration

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

- acoustic calibrator (12 months);
- microphone (24 months);
- integrating sound level meter (24 months);
- spectrum analyzer (36 months);
- data recording/playback system (24 months);
- anemometer (24 months);
- electric power transducer (24 months).

If the acoustic calibrator is calibrated as a part of the integrating sound level meter, the maximum calibration interval may be extended to 24 months.

An instrument shall always be recalibrated if it has been repaired or is suspected of fault or damage.

7 Measurements and measurement procedures

7.1 Measurement positions

To fully characterize the noise emission of a wind turbine, the following measurement positions are required.

7.1.1 Acoustic measurement positions

One, and optionally another three, microphone positions are to be used. The four positions shall be laid out in a pattern around the vertical centreline of the wind turbine tower as indicated in the plan view shown in Figure 3. The required downwind measurement position is identified as the reference position, as shown in Figure 3. The direction of the positions shall be accurate within ±15° relative to the wind direction at the time of measurement. The horizontal distance R_0 from the wind turbine tower vertical centreline to each microphone position shall be as shown in Figure 3, with a tolerance of 20 % and shall be measured with an accuracy of ±2 %.

As shown in Figure 4a), the reference distance R_0 for horizontal axis turbines is given by:

$$R_0 = H + \frac{D}{2} \tag{1}$$

where

H is the vertical distance from the ground to the rotor centre; and

D is the diameter of the rotor.

As shown in Figure 4b), the reference distance R_0 for vertical axis wind turbines is given by:

$$R_0 = H + D \tag{2}$$

where

H is the vertical distance from the ground to the rotor equatorial plane; and

D is the equatorial diameter.

To minimize influence due to the edges of the reflecting board on the measurement results, it shall be ensured that the board is positioned flat on the ground. Any edges or gaps under the board should be levelled out by means of soil. The inclination angle ϕ, as shown in Figure 4, shall be between 25° and 40°. This may require adjustment of the measurement position within the tolerances stated above.

The measurement position shall be chosen so that the calculated influence from any reflecting structures, such as buildings or walls, shall be less than 0,2 dB.

7.1.2 Wind speed and direction measurement positions

The test anemometer and wind direction transducer shall be mounted in the upwind direction of the wind turbine at a height between 10 m and rotor centre. The transducers shall be placed at a distance between 2D and 4D from the rotor centre. If method 2 (see 7.3.1.2) is used to determine the wind speed, the allowable region in which the anemometer and wind direction transducer shall be located is given in Figure 5.

The angle β is given by:

$$\beta = \frac{z - z_{ref}}{H - z_{ref}}\left(\beta_{max} - \beta_{min}\right) + \beta_{min} \tag{3}$$

where

z is the anemometer height, see Figure 6;

z_{ref} is the reference height of 10 m;

H is the height of the rotor centre or equatorial plane of the wind turbine, see Figure 4;

β_{max} is the maximum angle for β, $\beta_{max} = 90^{o}$;

β_{min} is the minimum angle for β, $\beta_{min} = 30^{o}$.

During the course of the measurements, the test anemometer shall not be within the wake of any portion of any other wind turbine rotor or other structure. The wake of a wind turbine shall be considered to extend 10 rotor diameters downwind of the wind turbine. The wind speed and wind direction transducers shall be placed so that they do not interfere with each other.

If 95 % of the rated power is reached below a standardized wind speed of 10 m/s and the nacelle anemometer method is chosen, the wind speed from the nacelle anemometer shall be measured. If no nacelle anemometer is available, an anemometer shall be mounted on the nacelle. For wind turbines with a hub height below 30 m, all wind speed measurements may be taken from an anemometer between 10 m and hub height.

7.2 Acoustic measurements

The acoustic measurements shall permit the following information to be determined about the noise emission from the wind turbine at the integer wind speeds 6, 7, 8, 9 and 10 m/s (wind speed at 10 m height and roughness length of 0,05 m):

– the apparent sound power level;
– the one-third octave band levels;
– the tonality.

Optional measurements may include directivity, infrasound, low-frequency noise and impulsivity.

7.2.1 Acoustic measurement requirements

For all acoustic measurements, the following requirements are valid:

- The complete measurement chain shall be calibrated at least at one frequency before and after the measurements, or if the microphones are disconnected during repositioning.
- All acoustical signals must be recorded and stored for later analysis.
- Periods with intruding intermittent background noise (as from aircraft) shall be omitted.
- With the wind turbine stopped, and using the same measurement set-up, the background noise shall be measured immediately before or after each measurement series of wind turbine noise and during similar wind conditions. When measuring background noise, every effort shall be made to ensure that the background sound measurements are representative of the background noise that occurred during the wind turbine noise emission measurements
- The measurements shall cover as broad a range of wind speeds as practically possible. To obtain a sufficient range of wind speeds it may be necessary to take the measurements in several measurement series.

Additionally, the following requirements are valid for the individual acoustic measurements.

7.2.2 Acoustic measurements at the reference position 1

7.2.2.1 A-weighted sound pressure level

The equivalent continuous A-weighted sound pressure level of the noise from the wind turbine shall be measured at the reference position by a series of at least 30 measurements concurrent with measurements of the wind speed. Each measurement shall be integrated over a period of not less than 1 min. At least three measurements shall be within ±0,5 m/s at each integer wind speed.

For the background noise at least 30 measurements in total shall be made, covering corresponding ranges of wind speed as above.

7.2.2.2 One-third octave band measurements

The one-third octave band spectrum of the noise from the wind turbine in the reference position shall be determined as the energy average of at least three spectra, each measured over at least 1 min at each integer wind speed. As a minimum, one-third octave bands with centre frequencies from 50 Hz to 10 kHz, inclusive, shall be measured.

Background measurements with the wind turbine stopped shall satisfy the same requirements.

7.2.2.3 Narrow band measurements

For each integer wind speed, at least 2 min of A-weighted wind turbine noise and background noise are required. These 2 min shall be as close as possible to the integer wind speeds. If the A-weighting cannot be applied during measurement, linear spectra may be converted to A-weighted spectra according to IEC 61672-1:2002.

7.2.3 Optional acoustic measurements at positions 2, 3 and 4

The equivalent continuous A-weighted sound pressure level of the noise from the wind turbine shall be measured in the non-reference position by one of the following two methods.

In the first (preferred) method, the measurements in the non-reference positions shall be made simultaneously with corresponding measurements in the reference position. The measurements in the three non-reference positions may be made individually, but each one shall be made simultaneously with measurement in the reference position. The sound pressure level at each position shall be determined as the energy average of five measurements each integrated over at least 1 min. The five periods with an average wind speed closest to 8 m/s shall be used.

The background noise measurements shall be energy averaged over five periods of at least 1 min.

In the second method, simultaneous measurements are not required. The equivalent continuous A-weighted sound pressure level of the noise from the wind turbine in each of the three non-reference positions shall be measured as a series of at least 10 measurements, each energy averaged over at least 1 min concurrent with wind speed measurements. During the measurements, the wind speed V_s shall differ by less than 2 m/s from 8 m/s, and at least 25 % of the measurements shall be above, and 25 % below, 8 m/s.

With the wind turbine stopped, at least 10 background measurements, each energy averaged over at least 1 min, shall be obtained.

7.2.4 Other optional measurements

It is recommended that additional measurements be taken to quantify noise emissions that have definite character that is not described by the measurement procedures detailed in this standard.

Such character might be the emission of infrasound, low-frequency noise, low-frequency modulation of broadband noise, impulses, or unusual sounds (such as a whine, hiss, screech or hum), distinct impulses in the noise (for example bangs, clatters, clicks, or thumps), or noise that is irregular enough in character to attract attention. These areas are discussed, and possible quantitative measures outlined in Annex A. These measures are not universally accepted and are given for guidance only.

7.3 Non-acoustic measurements

The following non-acoustic measurements shall be made.

7.3.1 Wind speed measurements

The wind speed shall be determined according to one of the following two methods. Method 1 is the preferred method and is mandatory for certification and declaration measurements.

7.3.1.1 Method 1: determination of the wind speed from the electric output and the power curve

The power curve relates the power to the wind speed at hub height. For most wind turbines, the wind speed can be determined from the measured electric power. Correlation between measured sound level and measured electric power is very high up to the point of maximum power.

The wind speed shall be obtained from measurements of the produced electric power using a traceable power versus wind speed curve, preferably measured according to IEC 61400-12, and preferably for the same turbine or, otherwise, for the same type of wind turbine with the same components and adjustments. The power curve shall give the relation between the wind speed at hub height and the electric power that the turbine produces for standard atmospheric conditions of 15 °C and 101,3 kPa.

Electric power shall be averaged over the same period as the noise measurements.

The use of power measurements and the wind turbine power curve is the preferred method of wind speed determination, provided the wind turbine operates below the maximum power point during the noise measurement series. However, note that during background noise measurements, the wind speed must be measured with an anemometer at a height of at least 10 m.

Record the power produced by the wind turbine and confirm that for each noise sampling period, the power did not exceed 95 % of maximum power. Note that power values below 95 % of the maximum power may originate from high wind speeds above the wind speed where the wind turbine reaches rated power. This may be controlled by checking the measured wind speed.

For turbines with passive stall control, the electric power measured during the noise measurements shall be converted to standard atmospheric conditions, using the following equation:

$$P_n = P_m \left(\frac{T_k}{T_{ref}} \right) \frac{p_{ref}}{p} \tag{4}$$

where

P_n is the normalised electric power (kW);

P_m is the measured electric power (kW);

T_k is air temperature in K, $T_k = T_c + 273$;

T_c is the air temperature (°C);

T_{ref} is the reference temperature, T_{ref} = 288 K;

p is the atmospheric pressure (kPa);

p_{ref} is the reference atmospheric pressure, p_{ref} = 101,3 kPa.

The wind speed at rotor centre height obtained from the power curve at P_n shall be converted to a height of 10 m and the reference roughness length, as described in Equation (7).

For turbines with active power control, the wind speed at hub height shall be corrected according to:

$$V_H = V_D \left(\frac{p_{ref}\ T_k}{p\ T_{ref}} \right)^{\frac{1}{3}} \tag{5}$$

where

V_H is the corrected wind speed at hub height (m/s);

V_D is the derived wind speed from the power curve (m/s).

The corrected wind speed at hub height shall be converted to standardised wind speed at height of 10 m and the reference roughness length, as described in Equation (7).

If the standardised wind speed corresponding to 95 % of rated power is below 10 m/s, one of the following two methods shall be used to determine the wind speed for data above 95 % of rated power:

7.3.1.1.1 Nacelle anemometer method

For all data points between 5 % and 95 % of rated power, a linear regression using the nacelle wind speed V_n and corrected wind speed V_H at hub height determined from electrical power measurements shall be determined. For passive stall turbines, the corrected wind speed V_H at hub height is the derived wind speed V_D from power. For active power controlled turbine, V_H is determined from Equation (5).

The corrected wind speed above 95 % of rated power shall be determined applying the resulting linear regression to the nacelle wind speed V_n.

7.3.1.1.2 κ-factor method

For all data points with power levels below 95 % of rated power, the ratio of standardised wind speed and measured wind speed, κ, shall be derived. This ratio shall then be applied to the measured wind speed of the data points with power levels above 95 % of rated power to estimate the standardised wind speed using Equation (6).

$$V_s = \kappa V_z \tag{6}$$

where

V_s is the standardised wind speed;

V_z is the wind speed measured at anemometer height *z*.

The nacelle anemometer method is the preferred method as the correlation between nacelle wind speed and the electrical power output is typically better than for the wind speed measured below hub height.

7.3.1.2 Method 2: determination of wind speed with an anemometer

If an anemometer is used to measure wind speeds, the wind speed measurement results shall be adjusted to a height of 10 m and the reference roughness length as described in Equation (7).

Measurement by an anemometer at a height between 10 m and hub height will also be appropriate during background noise measurements, when the wind turbine is parked, and the turbine has been used as an anemometer during the turbine noise measurements.

Wind speed data shall be collected and arithmetically averaged over the same period as the acoustic measurements.

7.3.2 Wind direction

Wind direction will be observed from a wind direction transducer to ensure that measurement locations are kept within 15° of nacelle azimuth positions with respect to upwind, and to measure the position of the anemometer. Wind direction shall be averaged over the same period as the noise measurements.

7.3.3 Other atmospheric conditions

Air temperature and pressure shall be measured and recorded at least every 2 h.

Turbulence in the wind incident to a wind turbine can affect its aerodynamic noise emission. A discussion of assessment of turbulence is contained in Annex C.

7.3.4 Rotor speed and pitch angle measurement

Measurement and reporting of relevant wind turbine control parameters such as rotor speed and pitch angle are recommended. These data may be obtained from the wind turbine controller.

8 Data reduction procedures

8.1 Wind speed

The wind speeds measured at height z or determined at rotor centre height H from measurements of electrical power shall be corrected to the wind speed V_s at reference conditions by assuming wind profiles in the following equation:

$$V_s = V_z \left[\frac{\ln\left(\frac{z_{ref}}{z_{0ref}}\right) \ln\left(\frac{H}{z_0}\right)}{\ln\left(\frac{H}{z_{0ref}}\right) \ln\left(\frac{z}{z_0}\right)} \right] \quad (7)$$

where

z_{0ref} is the reference roughness length of 0,05 m;

z_0 is the roughness length;

H is the rotor centre height;

z_{ref} is the reference height, 10 m;

z is the anemometer height.

Equation (7) uses the following principles:

– the correction for the measured height z to the rotor centre height H uses a logarithmic wind profile with the site roughness length z_0 to account for the actual site conditions.

– the correction from rotor centre height H to reference conditions uses a logarithmic wind profile with a reference roughness length z_{0ref}. This describes the noise characteristic independent of the terrain.

The roughness length z_0 can be calculated from wind speed measurements of several heights or estimated according to Table 1. If the preferred method (Method 1) is used to determine wind speed, κ may also be used to calculate the standardised wind speed for background noise measurements.

Table 1 – Roughness length

Type of terrain	Roughness length z_0
Water, snow or sand surfaces	0,000 1 m
Open, flat land, mown grass, bare soil	0,01 m
Farmland with some vegetation	0,05 m
Suburbs, towns, forests, many trees and bushes	0,3 m

8.2 Correction for background noise

Using the methods specified in the relevant following paragraphs 8.3 to 8.5, all measured sound pressure levels shall be corrected for the influence of background noise. For average background sound pressure levels that are 6 dB or more below the combined level of the wind turbine and background, the corrected value can be obtained using the following equation:

$$L_s = 10\lg\left[10^{\left(0{,}1L_{s+n}\right)} - 10^{\left(0{,}1L_n\right)}\right] \tag{8}$$

where

L_s is the equivalent continuous sound pressure level, in dB, of the wind turbine operating alone;

L_{s+n} is the equivalent continuous sound pressure level, in dB, of the wind turbine plus background noise;

L_n is the background equivalent continuous sound pressure level, in dB.

If the equivalent continuous sound pressure level of the wind turbine plus background noise, L_{s+n}, is less than 6 dB but more than 3 dB higher than the background level, L_{s+n} is corrected by subtraction of 1,3 dB, but the corrected data points are marked with an asterisk, " * ". These data points shall not be used for the determination of the apparent sound power level or directivity. If the difference is less than 3 dB, no data points shall be reported, but it shall be reported that the wind turbine noise was less than the background noise.

8.3 Apparent sound power levels

The analyst shall use a 4th order regression as long as the correlation coefficient is 0,8 or greater. Otherwise bin analysis shall be utilized using linear regression within bins to determine the sound pressure levels at the integer wind speeds. The bins will be 1 m/s wide, open on the low end, closed on the high end. There shall be at least one point on both sides of the integer wind speed. From this analysis, the value of $L_{Aeq,k}$ at the each integer wind speed from 6 m/s to 10 m/s shall be determined. $L_{Aeq,k}$ is the value of the fitted second order regression at the integer wind speed.

A similar regression analysis with the 30 or more data pairs of the background noise measurements shall be made. The value of $L_{Aeq,k}$ at the integer wind speeds shall be corrected for the background noise at the integer wind speeds and shall be identified as $L_{Aeq,c,k}$.

The apparent sound power level, $L_{WA,k}$, is calculated from the background corrected sound pressure level, $L_{Aeq,c,k}$ at the integer wind speeds at the reference position as follows:

$$L_{WA,k} = L_{Aeq,c,k} - 6 + 10\lg\left[\frac{4\pi R_1^2}{S_0}\right] \tag{9}$$

where

$L_{Aeq,c,k}$ is the background corrected A-weighted sound pressure level at the integer wind speeds and under reference conditions;

R_1 is the slant distance in meters from the rotor centre to the microphone as shown in Figure 4; and

S_0 is a reference area, S_0 = 1 m^2.

The 6 dB constant in equation (9) accounts for the approximate pressure doubling that occurs for the sound level measurements on a ground board.

8.4 One-third octave band levels

The one-third octave band levels of the wind turbine noise shall be corrected for the corresponding one-third octave band levels of the background noise.

8.5 Tonality

8.5.1 General methodology

The presence of tones in the noise at different wind speeds shall be determined on the basis of the narrowband analysis.

The tonal analysis shall cover the same wind speed range as the sound power level measurement. For each wind speed bin, the two one-minute periods closest to the integer wind speed value shall be analysed as shown in Figure 7.

The two one-minute measurements shall be divided into 12 ten-second periods, from which 12 energy averaged narrowband spectra using the Hanning window are obtained.

The frequency resolution shall be within the range shown in Table 2.

Table 2 – Frequency resolution

Frequency Hz	**Less than 2 000**	**2 000 – 5 000**
Frequency resolution	2 to 5 Hz	2 to 12,5 Hz

For each 10-second energy averaged spectrum, j = 1 to 12, in each integer wind speed, k = 6, 7, 8, 9, 10:

- The sound pressure level $L_{\mathrm{pt,j,k}}$ of the tone(s) shall be determined.
- The sound pressure level of the masking noise $L_{\mathrm{pn,j,k}}$ in a critical band around the tone shall be determined.
- The tonality $\Delta L_{\mathrm{tn,j,k}}$, the difference between the sound pressure level of the tone and the masking noise level, shall be found.

The overall tonality, ΔL_{k}, is determined as the energy average of the 12 individual $\Delta L_{\mathrm{tn,j,k}}$.

The bandwidth of a critical band shall be determined by:

$$\text{Critical bandwidth} = 25 + 75\left(1 + 1{,}4\left[\frac{f_{\mathrm{c}}}{1000}\right]^{2}\right)^{0{,}69} \qquad (10)$$

where f_{c} is the centre frequency in Hz.

In exceptional cases (for example very broad tones consisting of many lines or masking noise with very steep gradients) this method may not give the correct results. In such cases, deviations from the prescribed method may be needed and must be reported.

8.5.2 Identifying possible tones

A preliminary identification of tones is needed for the classification of the spectrum lines.

The following procedure is used to identify possible tones:

- find local maxima in the spectrum;
- calculate the average energy in the critical band centred on each local maximum, not including the line of the local maximum and the two adjacent lines;
- if the local maximum is more than 6 dB above the average masking noise level, then it is a possible tone.

8.5.3 Classification of spectral lines within the critical band

The critical band shall be positioned with centre frequency coincident with the possible tone frequency. For possible tones with frequencies between 20 Hz and 70 Hz, the critical band is 20 Hz to 120 Hz.

Within each critical band, every spectral line is classified as tone, masking, or neither, using the following procedure.

a) Calculate the $L_{70\ \%}$ sound pressure level, where $L_{70\ \%}$ is the energy average of the 70 % of spectral lines in the critical band with the lowest levels as shown in Figure 8.

b) Define a criterion level equal to the $L_{70\ \%}$ level plus 6 dB as illustrated in Figure 9;

  - A line is classified as 'masking' if its level is less than the criterion level. $L_{pn,avg}$ is then the energy average of all the lines classified as masking as illustrated in Figure 10.
  - A line is classified as 'tone' if its level exceeds $L_{pn,avg}$ plus 6 dB.
  - Where there are several adjacent lines classified as 'tone', the line having the greatest level is identified. Adjacent lines are then only classified as 'tone' if their levels are within 10 dB of the highest level.
  - A line is classified as 'neither' if it cannot be classified as either 'tone' or 'masking'. Spectral lines identified as 'neither' are ignored in further analysis. Figure 11 illustrates the classification of lines in a critical band.

8.5.4 Determination of the tone level

The sound pressure level of the tone, $L_{pt,j,k}$ is determined by energy summing all spectral lines identified as tones within the critical band in 8.5.3. Where this involves 2 or more adjacent lines, a correction is applied for using the Hanning window. This requires dividing the energy sum by 1,5.

Note that if more than one tone is present within the same critical band, the above procedure is equivalent to energy summing the level of these individual tones.

8.5.5 Correction for background noise

A 2-minute narrowband spectrum shall be made of the background noise using the two 1-minute measurements closest to the integer wind speed. For comparison with the corresponding analysis of the wind turbine noise, it must be ensured that the tones do not originate from the background noise. $L_{pn,avg,j,k}$ shall be corrected according to equation (8), using the level of the background noise in the same critical band and integer wind speed as used during the tone analysis. The background noise level is calculated from the energy sum of all lines in the critical band. The background noise level shall be at least 6 dB lower than the wind turbine noise in the relevant critical bands. If this is not the case, a statement must be recorded that the masking noise is influenced by background noise.

8.5.6 Determination of the masking noise level

The masking noise level, $L_{pn,j,k}$, is defined as follows:

$$L_{pn,j,k} = L_{pn,avg,j,k} + 10 \lg \left[\frac{\text{Critical bandwidth}}{\text{Effective noise bandwidth}} \right] \quad (11)$$

where $L_{pn,avg,j,k}$ is the background corrected energy average of the spectral lines identified as 'masking' within the critical band.

The effective noise bandwidth is 1,5 times the frequency resolution, which includes a correction for the use of the Hanning window.

8.5.7 Determination of tonality

The difference between the tone level, $L_{pt,j,k}$ and the level of the masking noise in the corresponding critical band, is given by:

$$\Delta L_{tn,j,k} = L_{pt,j,k} - L_{pn,j,k} \quad (12)$$

If no tone was identified according to 8.5.3 for some of the 12 ten-second spectra so that $\Delta L_{tn,j,k}$ is undefined, it shall be replaced by the following value:

$$\Delta L_{tn,j,k} = -10 \lg \left[\frac{\text{Critical bandwidth}}{\text{Effective noise bandwidth}} \right] \quad (13)$$

The 12 $\Delta L_{tn,j,k}$ are energy averaged to one ΔL_k, k = 6, 7, 8, 9, 10 for each wind speed bin.

Tones in different spectra with frequencies within 10 % of the critical bandwidth shall be regarded as the same tone. In this case, the average frequency is used for determining the audibility.

8.5.8 Audibility

For each value of ΔL_k, a frequency dependent correction must be applied to compensate for the response of the human ear to tones of different frequency.

The 'tonal audibility', $\Delta L_{a,k}$, is defined as:

$$\Delta L_{a,k} = \Delta L_k - L_a \quad (14)$$

L_a is the frequency dependent audibility criterion, defined as:

$$L_a = -2 - \lg \left[1 + \left(\frac{f}{502} \right)^{2,5} \right] \quad (15)$$

where f is the frequency of the tone, in Hz.

Note that this criterion curve has been determined from listening tests, and reflects the subjective response of a 'typical' listener to time-invariant tones of different frequencies.

A corresponding value of $\Delta L_{a,k}$ must be calculated for each value of ΔL_k. For tonal audibilities meeting the condition:

$$\Delta L_{a,k} \geq -3{,}0 \text{ dB} \tag{16}$$

The values of $\Delta L_{a,k}$ shall be reported.

For tonal audibilities not meeting this condition, i.e. where:

$$\Delta L_{a,k} < -3{,}0 \text{ dB} \tag{17}$$

there is no requirement to report the values.

8.6 Directivity (optional)

The directivity of the wind turbine noise in the directions of the three positions 2, 3, and 4 should be determined from the A-weighted sound pressure levels in these positions, measured simultaneously with the A-weighted sound pressure level in the reference position 1. The levels shall be corrected for background noise and for the different distance. The directivity Δ_i at each position shall be determined by use of the equation:

$$\Delta_i = L_{Aeq,\,i} - L_{Aeq,1} + 20 \lg\left(\frac{R_i}{R_1}\right) \tag{18}$$

where

$L_{Aeq,i}$ is the A-weighted sound pressure level at positions 2, 3, or 4, corrected for background noise in the same position;

$L_{Aeq,1}$ is the A-weighted sound pressure level at reference position 1, measured simultaneously with $L_{Aeq,i}$ and also corrected for background noise;

R_i is the slant distance between the rotor centre and positions 2, 3, or 4; and

R_1 is the slant distance between the rotor centre and the reference position 1.

If the alternative measurement procedure with non-simultaneous measurements is used, the A-weighted sound pressure level of the wind turbine noise and of the background noise at the acoustic reference wind speed during the measurements in the reference position shall be determined by regression analysis for each of the measurement positions 1, 2, 3, and 4. The results of the wind turbine noise measurements shall be corrected for background noise and the directivity Δ_i at each position determined using equation (8).

9 Information to be reported

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

9.1 Characterisation of the wind turbine

The wind turbine configuration shall include the following information:

– Wind turbine details:
  - manufacturer;
  - model number;
  - serial number.
– Operating details:
  - vertical or horizontal axis wind turbine;
  - upwind or downwind rotor;
  - hub height;
  - horizontal distance from rotor centre to tower axis;
  - diameter of rotor;
  - tower type (lattice or tube);
  - passive stall, active stall, or pitch controlled turbine;
  - constant or variable speed;
  - power curve (if required for wind speed determination);
  - rotational speed at each integer standardised wind speed from 6 to 10 m/s and at rated power;
  - pitch angle at each integer standardised wind speed from 6 to 10 m/s;
  - rated power output;
  - control software version.
– Rotor details:
  - rotor control devices;
  - presence of vortex generators, stall strips, serrated trailing edges;
  - blade type;
  - number of blades.
– Gearbox details:
  - manufacturer;
  - model number;
  - fixed-parallel-shaft or planetary gearbox.
– Generator details:
  - manufacturer;
  - model number;
  - rotational speed.

9.2 Physical environment

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

- details of the site including location, site map and other relevant information;
- type of topography/terrain (hilly, flat, cliffs, mountains, etc.) in surrounding area (nearest 1 km);
- surface characteristics (such as grass, sand, trees, bushes, water surfaces);
- nearby reflecting structures such as buildings or other structures, cliffs, trees, water surfaces;
- other nearby sound sources possibly affecting background noise level, such as other wind turbines, highways, industrial complexes, airports;
- two photos, one taken in the direction of the turbine from the reference microphone position, and one taken from the wind mast toward the turbine;
- a photo of the microphone on the measurement board positioned on the ground and immediate surroundings, see Figure 2.

9.3 Instrumentation

The following information on the measurement instrumentation shall be reported:

- the manufacturer(s);
- the instrument name and type;
- serial number(s);
- other relevant information (such as last calibration date);
- anemometer position and measured height for each measurement series;
- influence of secondary wind screen, if used.

9.4 Acoustic data

The following acoustic data shall be reported:

- the measured position of each microphone for each measurement series;
- $L_{WA,k}$ at each integer wind speed from 6 to 10 m/s and a graph of background corrected normalised values. The axes of the graph shall be linear, and scaled such that 1 m/s corresponds to 2 dB;
- a plot showing all measured data pairs at position 1 of the wind turbine sound and background noise (with different symbols). On the plot, the axes of L_{Aeq} and V_s shall be linear, and scaled so that 1 m/s corresponds to 2 dB;
- table and plot of sound pressure spectrum in third octaves for each integer wind speed from 6 to 10 m/s; coordinates plotted at 1 octave = 10 dB, and levels marked with an asterisk as appropriate.

For each integer wind speed (k = 6, 7, 8, 9, 10):

- $\Delta L_{tn,j,k}$ (for j = 1, 2, 3,…12) for each identified tone;
- ΔL_k for each identified tone;
- $\Delta L_{a,k}$ for each identified tone;
- frequency of the tone(s);
- a typical 10 s energy averaged spectrum indicating the classification of spectral lines for each identified tone;
- time and date of each measurement series.

Optional acoustic data that may be reported includes:

- directivity;
- low frequency noise;
- infrasound;
- impulsivity;
- amplitude modulation;
- other noise characteristics, if any.

9.5 Non-acoustic data

The following non-acoustic data shall be reported:

- wind speed determination method;
- air temperature;
- atmospheric pressure;
- roughness length;
- the range of the wind direction during each measurement series (averages over 1 min periods).

Optional non-acoustic data that may be reported include:

- estimates or measurements of the turbulence intensity during acoustic measurements;
- whether the turbulence intensity data were determined by measurement or by inference from meteorological conditions;
- a plot showing the relation between the nacelle anemometer wind speed V_n and the wind speed V_H at hub height determined from measurements of electrical power.

9.6 Uncertainty

The uncertainty of the following reported acoustic quantities shall be assessed and reported:

- the apparent sound power level at integer wind speeds;
- one-third octave band spectrum of the noise at the reference position at each integer wind speed;
- the tonality of the sound emissions of the wind turbine measured at the reference position.

Guidance for the assessment of measurement uncertainty can be found in Annex D and in ISO document "Guide to the expression of uncertainty in measurement".

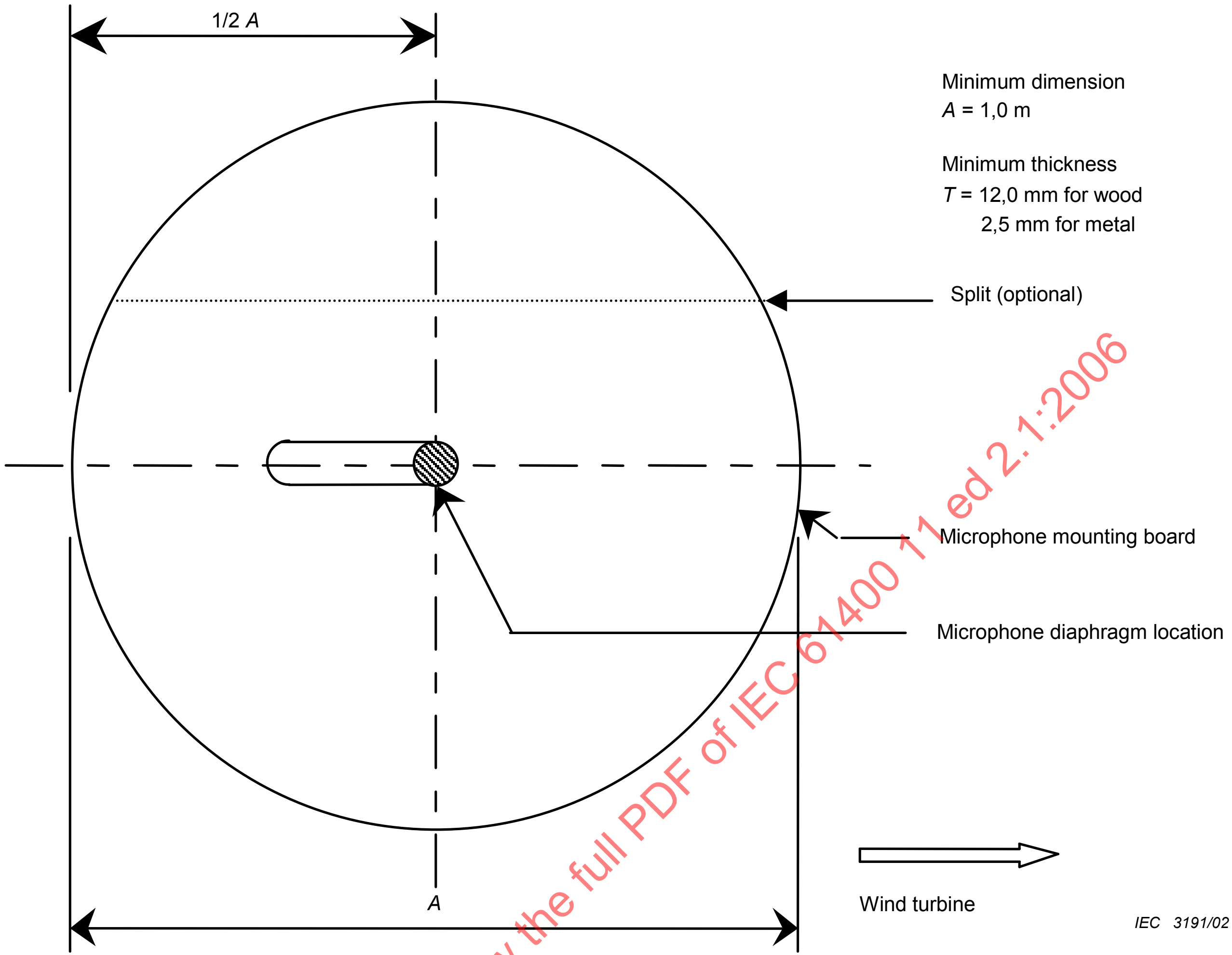

Figure 1a – Mounting of the microphone – plan view

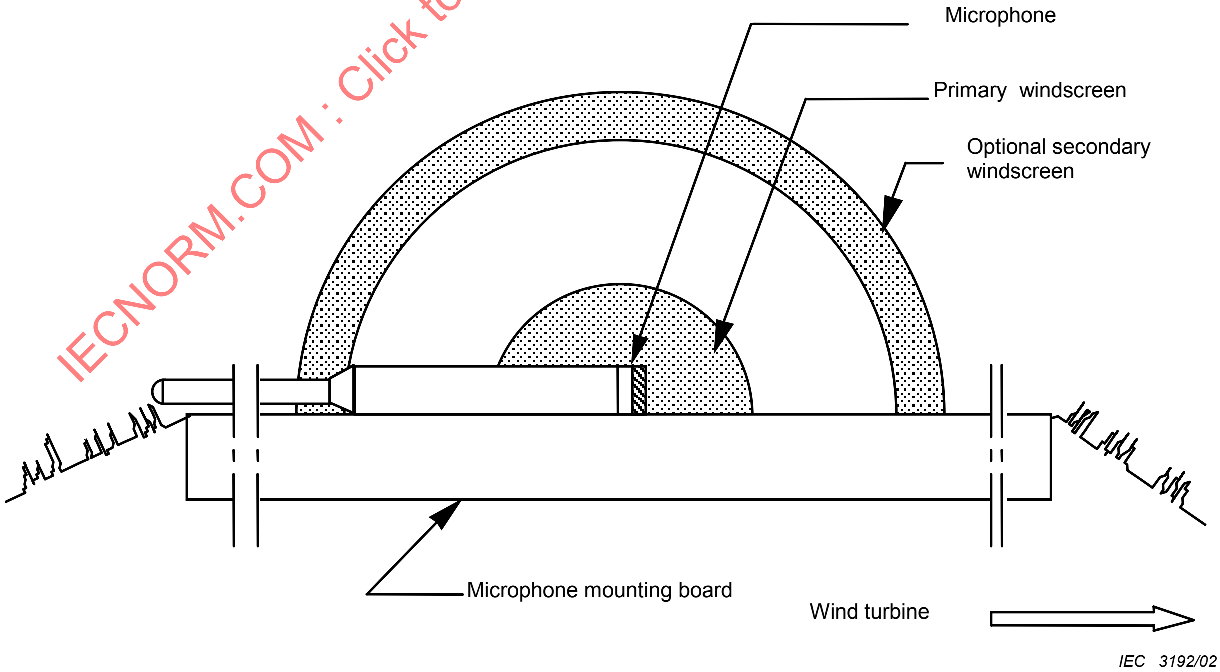

Figure 1b – Mounting of the microphone – vertical cross-section

Figure 1 – Mounting of the microphone

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Figure 2 – Picture of microphone and board

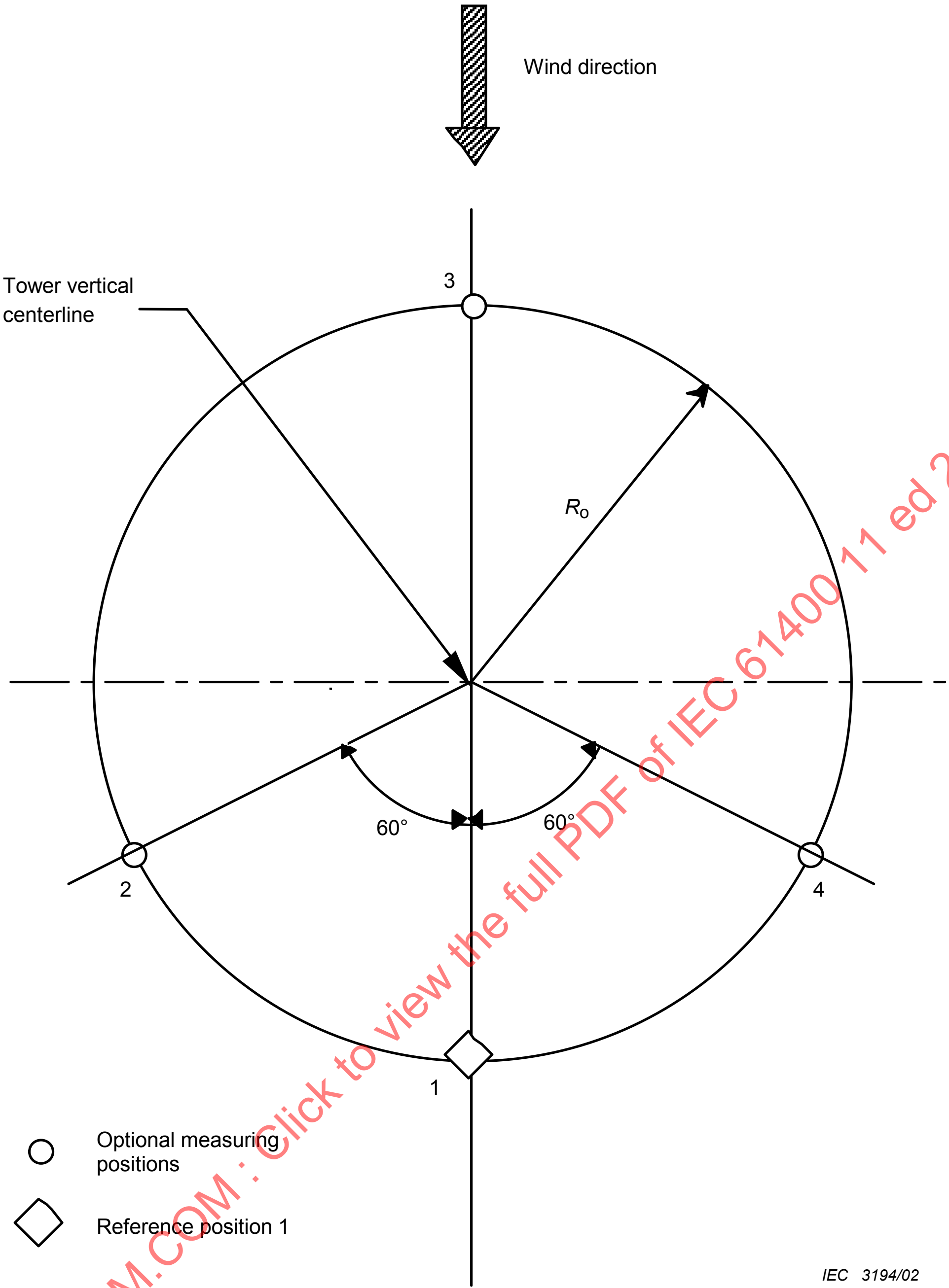


Figure 3 – Standard pattern for microphone measurement positions (plan view)

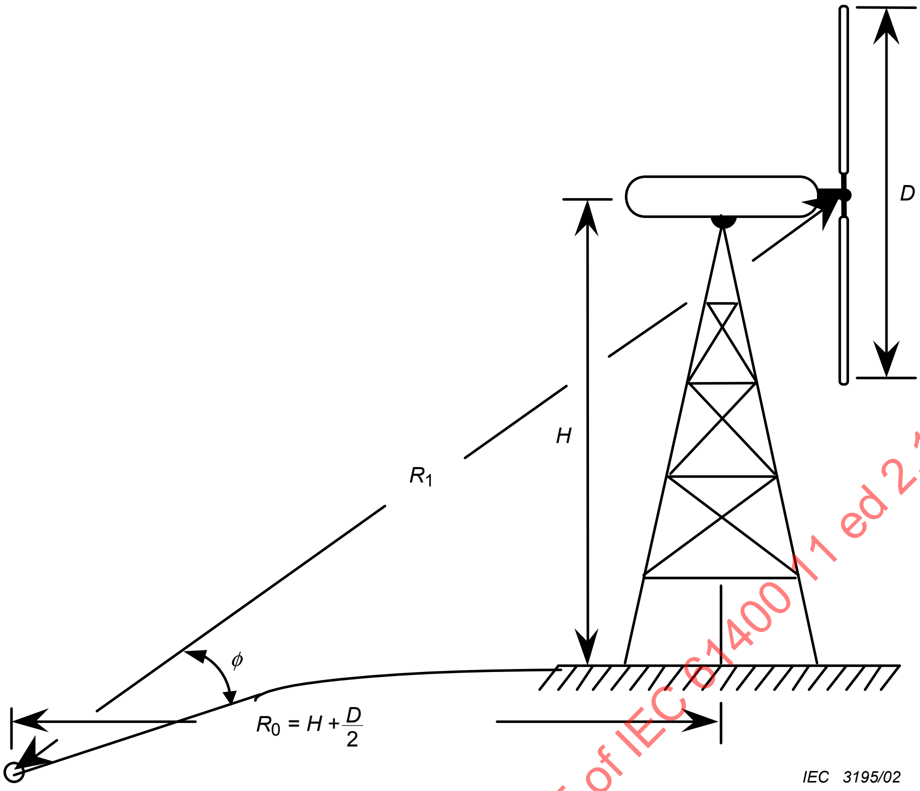


Figure 4a – Horizontal axis turbine

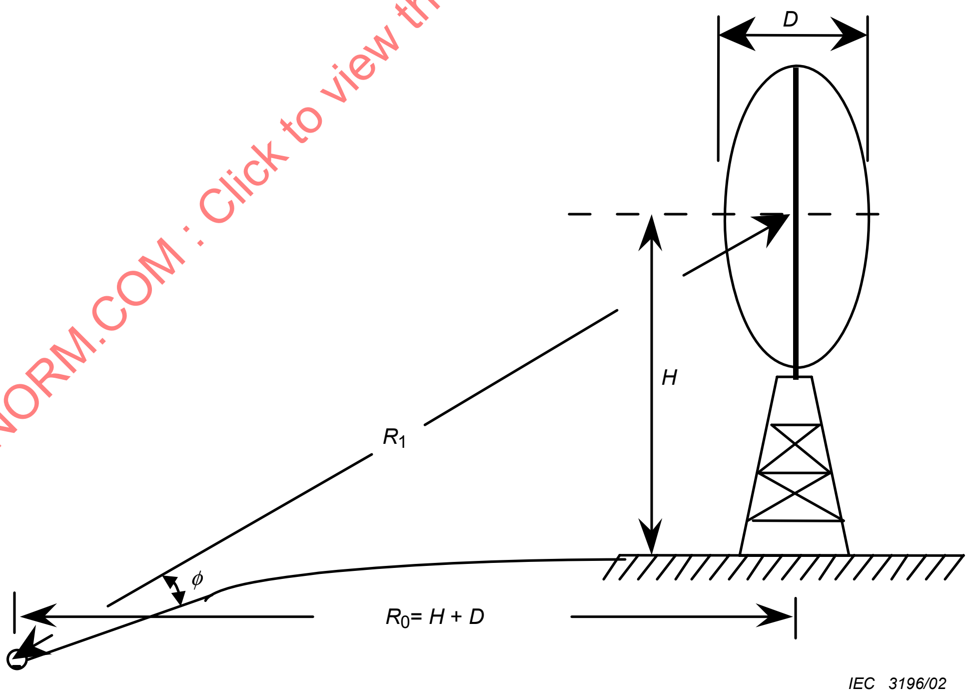
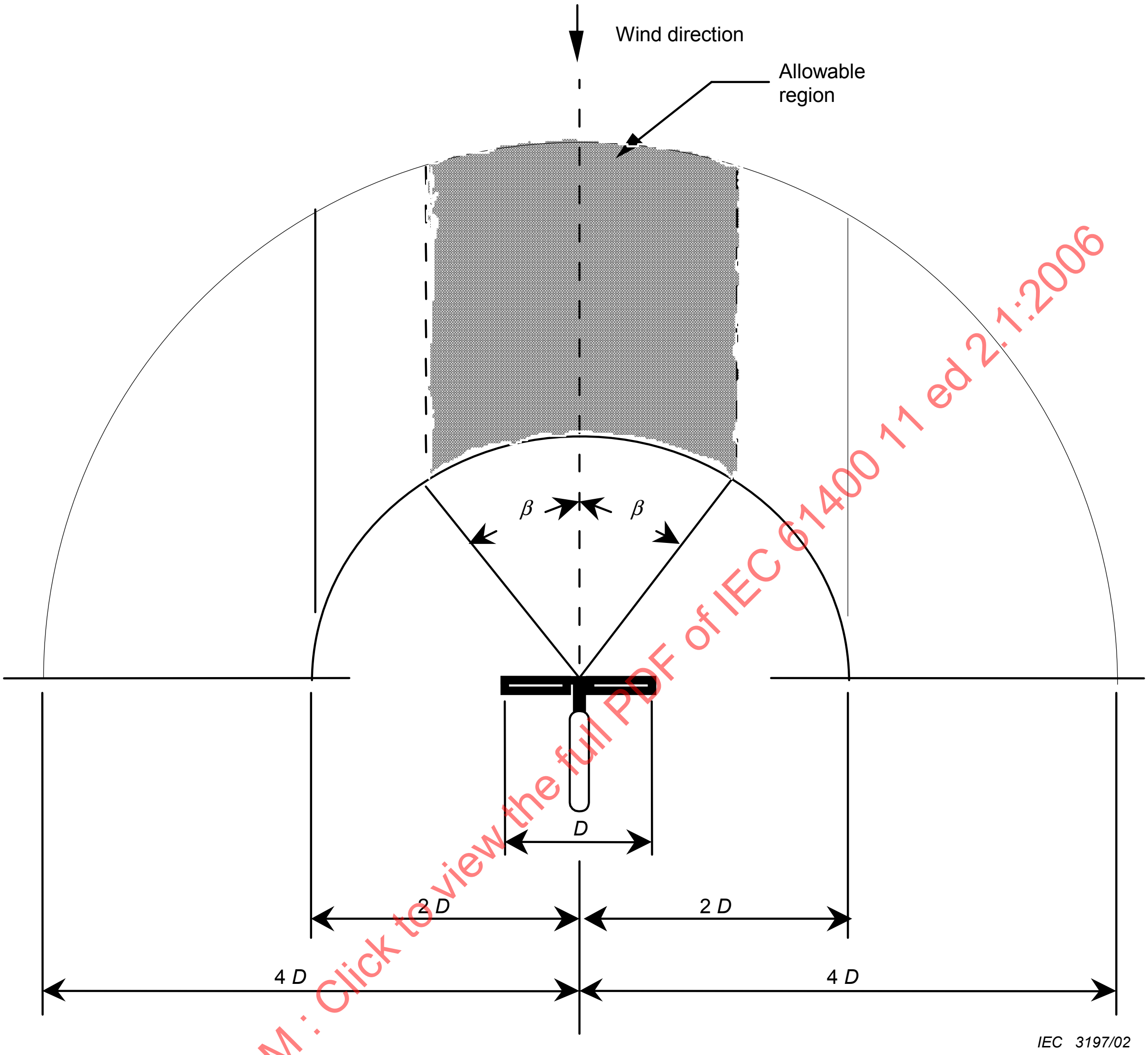


Figure 4b – Vertical axis turbine

Key

See 7.1.1.

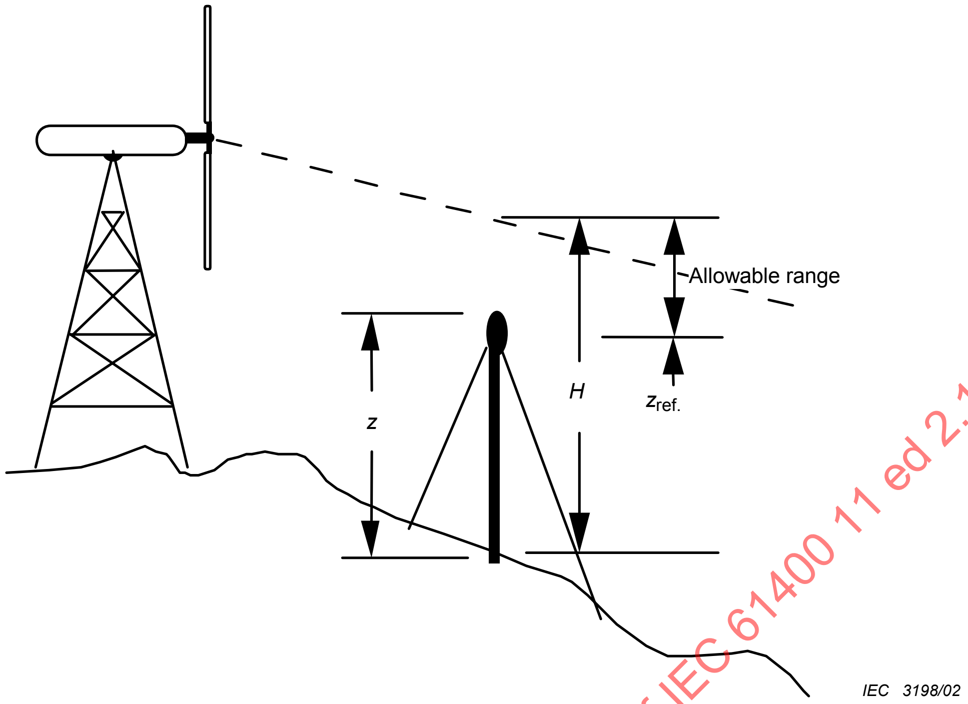
Figure 4 – Illustration of the definitions of R_0 and slant distance R_1



Key

See 7.1.2.

Figure 5 – Allowable region for meteorological mast position as a function of β – plan view



Key

See 7.1.2.

Figure 6 – Allowable range for anemometer height – cross section

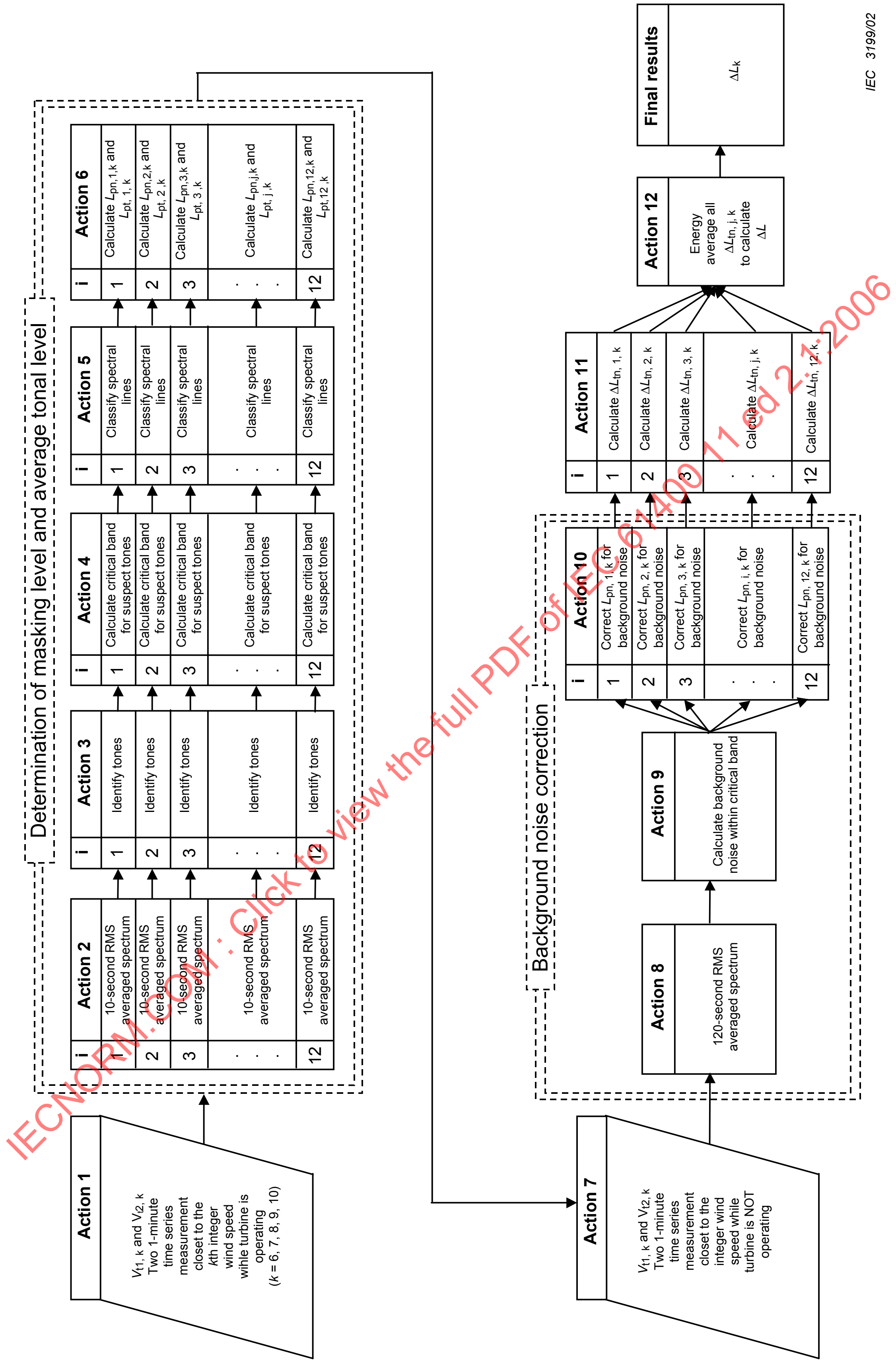


Figure 7 – Workflow chart for tonality procedure

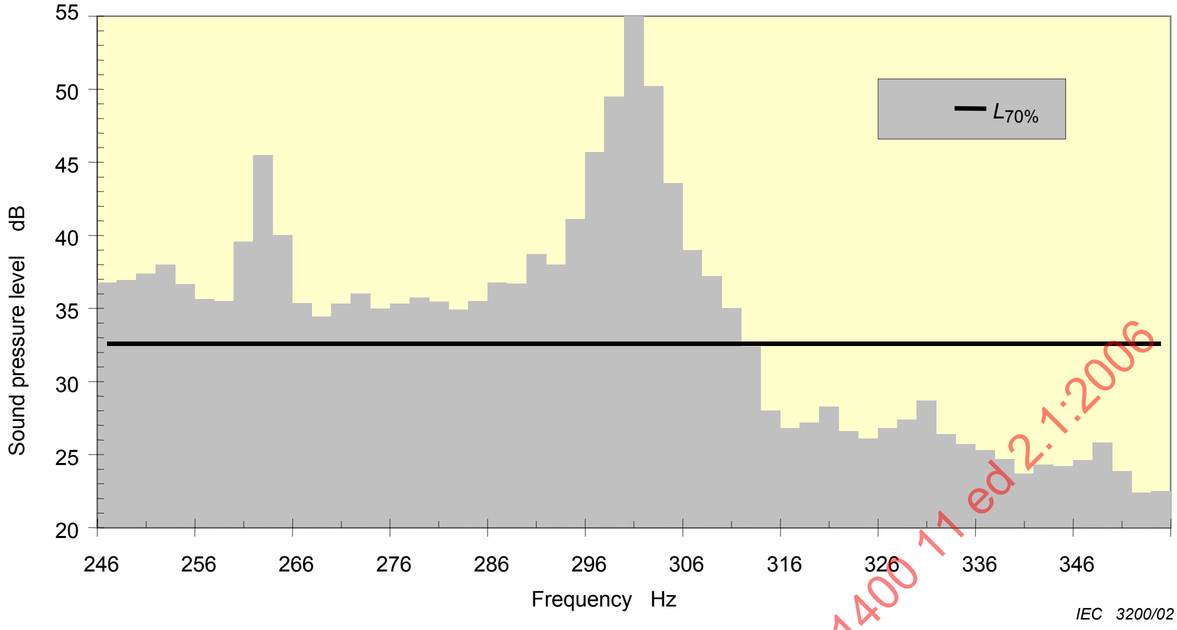


Figure 8 – Illustration of $L_{70\ \%}$ level in the critical band

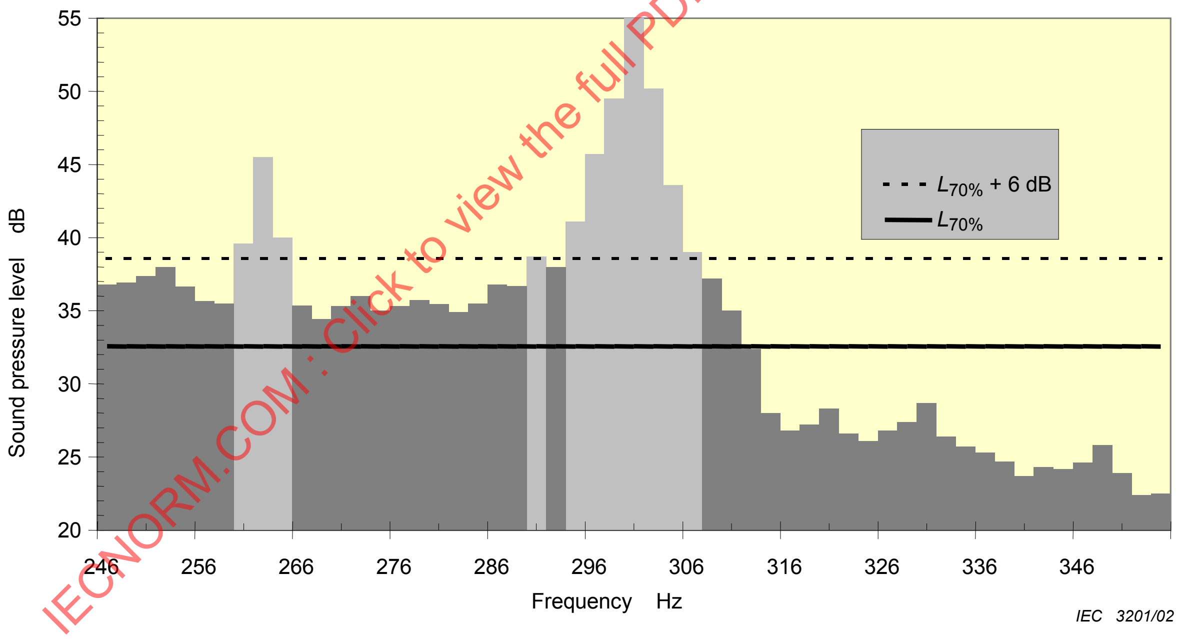


Figure 9 – Illustration of lines below the $L_{70\ \%}$ + 6 dB criterion

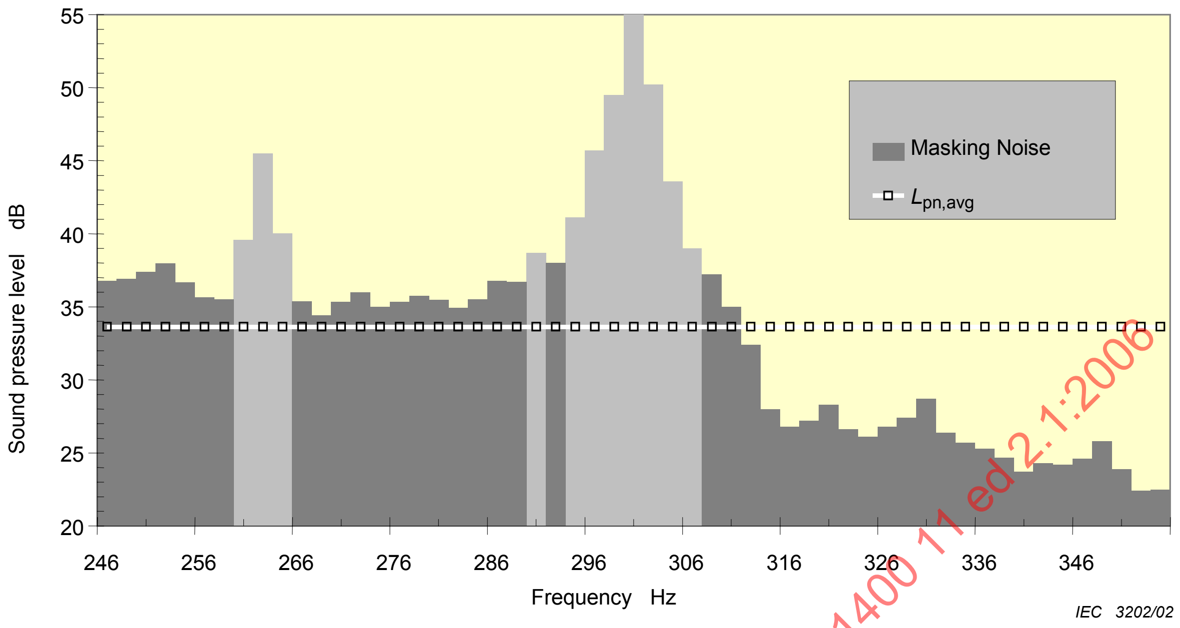


Figure 10 – Illustration of $L_{pn,avg}$ level and lines classified as masking

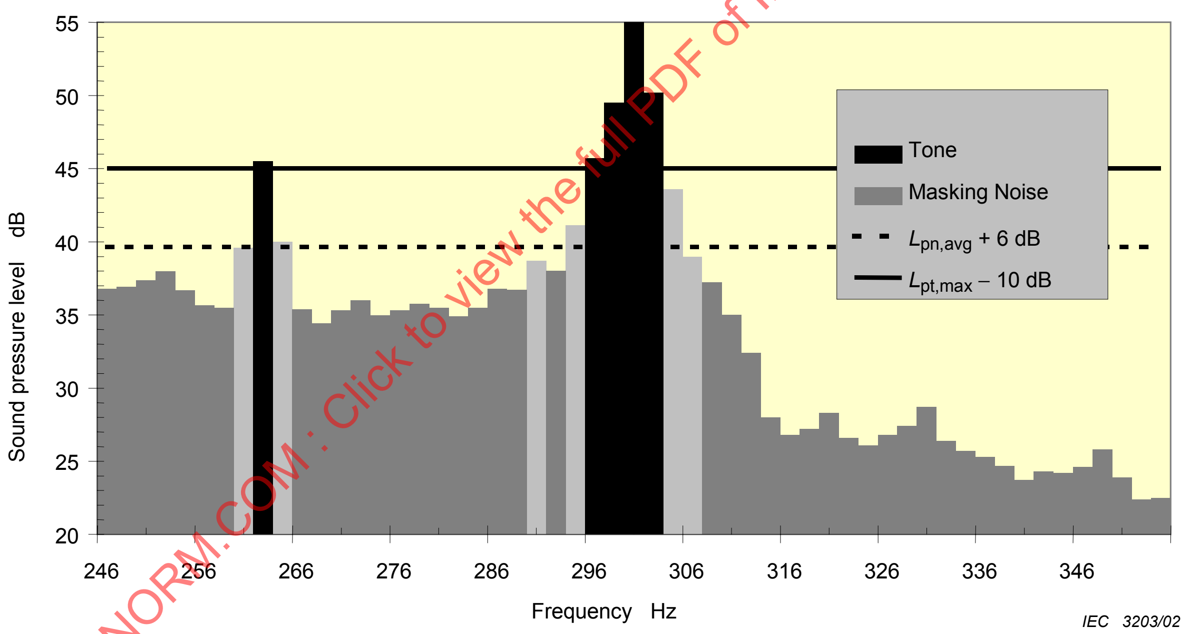


Figure 11 – Illustration of classifying all spectral lines

Annex A
(informative)

Other possible characteristics of wind turbine noise emission and their quantification

A.1 General

In addition to those characteristics of wind turbine noise described in the main text of this standard, the noise emission may also possess some, or all, of the following:

- infrasound;
- low-frequency noise;
- impulsivity;
- low-frequency modulation of broad band or tonal noise;
- other, such as a whine, hiss, screech or hum, etc., distinct impulses in the noise, such as bangs, clatters, clicks, or thumps, etc.

These areas are described briefly below, and possible quantitative measures discussed.

It should be noted that certain aspects of infrasound, low frequency noise, impulsivity and amplitude modulation are not fully understood at present. Thus it may prove that measurement positions farther away from the wind turbine than those specified in the standard may be preferable for the determination of these characteristics.

A.2 Infrasound

Sound at frequencies below 20 Hz is called infrasound. Although such sound is barely audible to the human ear, it can still cause problems such as vibration in buildings and, in extreme cases, can cause annoyance. If infrasound is thought to be emitted, an appropriate measure is the G-weighted sound pressure level according to ISO 7196.

A.3 Low frequency noise

A disturbance can be caused by low-frequency noise with frequencies in the range from 20 to 100 Hz. The annoyance caused by noise dominated by low frequencies is often not adequately described by the A-weighted sound pressure level, with the result that nuisance of such a noise may be underestimated if assessed using only an L_{Aeq} value.

It may be possible to decide whether the noise emission can be characterised as having a low-frequency component. This is likely to be the case if the difference between the A and C-weighted sound pressure levels exceeds approximately 20 dB.

In these circumstances, low-frequency noise may be quantified by extending the one-third octave band measurements described in the main body of the text, down to 20 Hz. For one-third octave bands, the 20, 25, 31,5 and 40 Hz bands should additionally be determined.

Narrowband spectra for frequencies below 100 Hz should be determined using a bandwidth smaller than one-half the blade passage frequency.