INTERNATIONAL STANDARD

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Wind turbine generator systems –

Part 11:
Acoustic noise measurement techniques

Aérogénérateurs –

Partie 11:
Techniques de mesure du bruit acoustique

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* See web site address on title page.

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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FOREWORD

1) The IEC (International Electrotechnical Commission) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of the IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, the IEC publishes International Standards. Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. The IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
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3) The documents produced have the form of recommendations for international use and are published in the form of standards, technical reports or guides and they are accepted by the National Committees in that sense.
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International Standard IEC 61400-11 has been prepared by IEC technical committee 88: Wind turbine systems.

The text of this standard is based on the following documents:

FDIS	Report on voting
88/96/FDIS	88/97/RVD

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

Annexes A, B, C, D and E are for information only.

A bilingual version of this standard may be issued at a later date.

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 (WTGS). This standard has been prepared with the anticipation that it would be applied by:

– the WTGS manufacturer striving to meet well defined acoustic emission performance requirements and/or a possible declaration system;

– the WTGS purchaser in specifying such performance requirements;

– the WTGS operator who may be required to verify that stated, or required, acoustic performance specifications are met for new or refurbished units;

– the WTGS planner or regulator who must be able to accurately and fairly define acoustical emission characteristics of WTGS 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 (WTGS). The standard will benefit those parties involved in the manufacture, installation planning and permitting, operation, utilization, and regulation of WTGS. The technically accurate measurement and analysis techniques recommended in this document should be applied by all parties to ensure that continuing development and operation of WTGS 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.

The consistency of results using the method for measurement of tonality will be assessed, and future revisions will address any identified shortcomings.

WIND TURBINE GENERATOR SYSTEMS –

Part 11: Acoustic noise measurement techniques

1 General

1.1 Scope and object

This part of IEC 61400 presents sound measurement procedures that enable noise emissions of a wind turbine to be characterized. 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 characterization of wind turbine noise with respect to a range of wind speeds and directions. Standardization of measurement procedures will also facilitate comparisons between different wind turbines.

The procedures present methodologies that will enable the noise emissions of a single WTGS to be characterized 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 WTGS 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 WTGS of a particular size or type. The procedures described in this standard allow for the thorough description of the noise emission from a WTGS. If, in some cases, less comprehensive measurements are needed, such measurements are made according to the relevant parts of this standard.

1.2 Normative references

The following normative documents contain provisions that, through reference in this text, constitute provisions of this part of IEC 61400. At the time of publication, the editions indicated were valid. All normative documents are subject to revision, and parties to agreements based on this part of IEC 61400 are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. Members of IEC and ISO maintain registers of currently valid International Standards.

IEC 60386:1972, *Method of measurement of speed fluctuations in sound recording and reproducing equipment*

IEC 60651:1979, *Sound level meters*

IEC 60688:1997, *Electrical measuring transducers for converting a.c. electrical quantities to analogue or digital signals*

IEC 60804:1985, *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*

1.3 Definitions

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

1.3.1

acoustic reference wind speed V_{aref} (in metres per second)

a wind speed of 8 m/s at reference conditions (10 m height, roughness length equal to 0,05 m) used in the calculation of the apparent sound power level to provide a uniform basis for the comparison of apparent sound power levels from different WTGS

1.3.2

apparent sound power level L_{WA} (in decibels)

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 as determined at the acoustic reference wind speed

1.3.3

A-weighted or C-weighted sound pressure levels (in decibels)

sound pressure levels measured with the A or C frequency weighting networks specified in IEC 60651, designated by L_A or L_C, respectively

1.3.4

directivity Δ_i (in decibels)

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 downstream from the turbine corrected to the same distance from the WTGS rotor centre

1.3.5

grazing angle ϕ (in degrees)

the angle between the plane of the microphone board and a line from the microphone to the rotor centre

1.3.6

reference distance R_0 (in metres)

the nominal horizontal distance from the centre of the base of the WTGS to each of the prescribed microphone positions

1.3.7

reference height z_{ref} (in metres)

a height of 10 m used for converting wind speed to reference conditions

1.3.8

reference roughness length z_{0ref} (in metres)

a roughness length of 0,05 m used for converting wind speed to reference conditions

1.3.9

sound pressure level L_p (in decibels)

10 times the logarithm to the base 10 of the ratio of the mean-square sound pressure to the square of the reference sound pressure of 20 µPa

1.3.10

standardized wind speed V_s (in metres per second)

wind speed converted to reference conditions (height 10 m and roughness length 0,05 m) using a logarithmic profile

1.3.11

tonality ΔL_{tn} (in decibels)

the difference between the tone level and the level of the masking noise in the critical band around the tone

1.4 Symbols and units

β	angle used to define allowable area for anemometer mast location	(°)
ϕ	grazing angle	(°)
D	rotor diameter (horizontal axis turbine) or equatorial diameter (vertical axis turbine)	(m)
Δ_i	directivity at "i th" position	(dB)
ΔL_{tn}	tonality	(dB)
f	frequency of tone	(Hz)
f_c	centre frequency of critical band	(Hz)
z	anemometer height	(m)
z_{ref}	reference height for wind speed, 10 m	(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}	equivalent continuous A-weighted sound pressure level	(dB)
$L_{Aeq,c}$	equivalent continuous A-weighted sound pressure level corrected for background noise at acoustic reference wind speed and corrected to reference conditions	(dB)
$L_{Aeq,i}$	equivalent continuous A-weighted sound pressure level in position "i" corrected for background noise	(dB)
L_n	equivalent continuous sound pressure level of the background noise	(dB)
L_p	sound pressure level	(dB)
L_{pn}	sound pressure level of masking noise within a critical band	(dB)
$L_{pn,avg}$	average of analysis bandwidth sound pressure levels of masking noise	(dB)
L_{pt}	sound pressure level of the tone or tones	(dB)
L_s	equivalent continuous sound pressure level of wind turbine noise alone	(dB)
L_{s+n}	equivalent continuous sound pressure level of combined wind turbine and background noise	(dB)
L_{WA}	apparent sound power level	(dB)
p	atmospheric pressure	(kPa)
P_m	measured electric power	(W)
P_n	normalised electric power	(W)
R_1	slant distance to reference position 1	(m)
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)
t	air temperature	(°C)
U_A, U_B, U_C	uncertainty components	(dB)
V_z	wind speed at height, z	(m/s)
V_{aref}	acoustic reference wind speed, 8 m/s	(m/s)
V_s	standardized wind speed	(m/s)
z_0	roughness length	(m)
z_{0ref}	reference roughness length, 0,05 m	(m)

1.5 Abbreviations

1.5.1 FFT Fast Fourier transform

1.5.2 WTGS Wind turbine generator system(s)

2 Outline of method

This part of IEC 61400 defines the procedures to be used in the measurement, analysis and reporting of acoustic emissions of WTGS. Instrumentation and calibration requirements are specified to ensure accuracy and consistency of acoustic and non-acoustic measurements. Non-acoustic measurements required to define 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 to obtain these parameters.

Application of the method described in this International Standard provides the value of the apparent A-weighted sound power level, its variation with wind speed and the directivity of an individual WTGS. Measurements include octave or third-octave band sound pressure levels, and narrow band spectra.

The measurements are made at locations close to the turbine in order to minimize the influence of terrain effects, atmospheric conditions or wind-induced noise. To account for the size of the WTGS under test, a reference distance R_0 based on the WTGS 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 minimize 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 adjusted to corresponding wind speeds at a reference height of 10 m and a reference roughness length of 0,05 m. The sound level at the acoustic reference wind speed of 8 m/s is determined based on a derived regression line correlating the sound levels and wind speeds. The apparent A-weighted sound power level is calculated from that sound level.

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 acoustic characteristics of WTGS noise that may be present (annex A);
– criteria for data recording and playback equipment (annex B);
– assessment of turbulence intensity (annex C);
– measurement uncertainty (annex D).

3 Instrumentation

3.1 Acoustic instruments

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

3.1.1 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.

3.1.2 Equipment for the determination of octave or 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 frequency range 45 Hz to 5 600 Hz. The filters shall meet the requirements of IEC 61260 for Class 1 filters.

The equivalent continuous sound pressure levels in octave or third-octave band shall be determined simultaneously with centre frequencies from 63 Hz to 4 kHz (third-octaves from 50 Hz to 5 kHz). It may be relevant to measure the low-frequency noise emission of a WTGS. In such cases, a wider frequency range is necessary, as discussed in annex A.

3.1.3 Equipment for the determination of narrow band spectra

The equipment shall fulfill the relevant requirements for IEC 60651 type 1 instrumentation in the frequency range 20 Hz to 5 600 Hz.

3.1.4 Microphone with reflecting surface and windscreen

The microphone shall be mounted 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 have a minimum width or diameter of 1,0 m and be made from a material that is acoustically hard, such as a piece of plywood or hard chip-board with a thickness of at least 12,0 mm, or a piece of metal with a thickness of at least 2,5 mm. If a rectangular board is used, the microphone shall be placed 100 mm to 150 mm from any line of symmetry.

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 shall 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 wind screen is used, the frequency response of the secondary wind screen mounted on a hard board must be documented.

3.1.5 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 fulfill the requirements of IEC 60942 class 1, and shall be used within its specified environmental conditions.

3.1.6 Data recording/playback systems

If a data recording/playback system is an integral part of the measurement instrumentation, the entire chain of measurement instruments shall fulfil the relevant requirements of IEC 60651, for type 1 instrumentation. Examples are given in annex B.

3.2 Non-acoustic instruments

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

3.2.1 Anemometers

The anemometer and its signal processing equipment shall have an a maximum deviation from the calibration value of ±0,5 m/s in the wind speed range from 3 m/s to 20 m/s. The anemometer shall be capable of measuring the average wind speed over time intervals synchronized with the noise measurements.

3.2.2 Electric power transducer

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

3.2.3 Wind direction transducer

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

3.2.4 Other instrumentation

Instruments to measure distance are required. Instruments to measure air temperature and atmospheric pressure are required for certain measurement procedures.

3.3 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.

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

4 Measurements and measurement procedures

4.1 Measurement positions

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

4.1.1 Acoustic measurement positions

Four microphone positions are to be used. The four positions shall be laid out in a pattern around the vertical centre-line of the WTGS tower as indicated in the plan view shown in figure 3. The 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:

$$R_0 = H + \frac{D}{2} \qquad (1)$$

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 :

$$R_0 = H + D \qquad (2)$$

where

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

D is the equatorial diameter.

The microphone mounting board shall be placed flat upon the ground with its longer axis (if any) pointing towards the wind turbine. The grazing 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.

4.1.2 Wind speed and direction measurement positions

The test anemometer and wind direction transducer shall be mounted in the upwind direction of the WTGS at a height between 10 m and rotor centre. The transducers shall be placed at a distance between 2 D and 4 D from the rotor centre. 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:

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

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, β_{max} = 90°;

β_{min} is the minimum angle for β, β_{min} = 30°.

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

4.2 Acoustic measurements

To fully characterize the noise emission of a WTGS, the following acoustic measurements are required.

4.2.1 Acoustic measurement requirements

The acoustic measurements shall permit the following information to be determined about the noise emission from the WTGS:

– the apparent sound power level;
– the dependence on wind speed;
– the directivity;
– the octave or third-octave band levels;
– the tonality.

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

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.

4.2.2 Acoustic measurements at the reference position 1

To fully characterize the noise emission of a WTGS, the following acoustic measurements shall be made at reference position 1.

4.2.2.1 A-weighted sound pressure level

The equivalent continuous A-weighted sound pressure level of the noise from the WTGS 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. Periods with intruding intermittent background noise (as from aircraft) shall be omitted. The measurements shall cover as broad a range of wind speeds, between cut-in and the wind speed where rated power is obtained, as practically possible. The range shall be at least 4 m/s (wind speed at 10 m height and roughness length of 0,05 m). To obtain a sufficient range of wind speeds it may be necessary to take the measurements in several measurement series. At least 10 of the measurements shall be taken during a wind speed not differing by more than 2 m/s from the acoustic reference wind speed. At least 25 % of the measurements shall be above and 25 % below the acoustic reference wind speed.

With the WTGS stopped, and using the same measurement set-up, the background noise shall be measured immediately before or after each measurement series of WTGS noise. In total at least 30 measurements shall be made, covering corresponding ranges of wind speed as stated above. 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.

4.2.2.2 Octave or third-octave band measurements

The octave or third-octave band spectrum of the noise from the WTGS in the reference position shall be determined as the energy average of five spectra, each measured over at least 1 min. As a minimum, the octave bands with centre frequencies from 63 Hz to 4 kHz, inclusive, shall be measured. During the measurement, the wind speed, averaged over each of the five periods, shall differ less than 2 m/s from the acoustic reference wind speed. There shall be periods in which the wind speed is below as well as above the acoustic reference wind speed. Periods with intruding intermittent background noise shall be omitted.

With the wind turbine stopped, the background noise shall be measured immediately before or after the WTGS noise full octave or third-octave band measurement, using the same measurement set-up and during similar wind conditions. The measurement shall be energy-averaged over at least five 1 min periods.

4.2.2.3 Narrow-band measurements

Narrow-band spectra of the sound from the WTGS shall be measured in the reference position 1 over a period of at least 2 min, when the wind speed averaged over the same period differs by less than 1 m/s from the acoustic reference wind speed. If, during the measurements, intruding intermittent background noises occur, these periods of intruding noise shall be omitted.

The effective noise bandwidth shall be less than the values shown in table 1.

If the measured sound contains widely spaced tones, it may be necessary to measure a number of spectra with different full-scale frequencies to obtain a sufficient frequency resolution equivalent to table 1. If there are closely spaced tone components, a finer resolution is necessary.

Table 1 – Effective noise bandwidth

Tone frequency Hz		20 – 63	63 – 200	200 – 630	630 – 2 000	2 000 – 5 000
Effective noise bandwidth	Absolute	20 Hz	20 Hz	20 Hz	22 Hz	57 Hz
	Relative	32 %	10 %	3,5 %	2,8 %	2 %

To determine the tonality of the WTGS, at least 200 contiguous spectra shall be measured, using a time weighting F (Fast) over a time period of at least 2 min. To determine the frequency of the tone or tones, as well as the masking noise level within the critical band around them, these specra shall be energy-averaged to produce a single, long-term spectrum. To determine the maximum tone level, 25 % of the spectra having the highest tone levels shall be identified and their tone levels shall be arithmetically averaged.

With real time analyzers, a linear integration period of 0,25 s approximates time weighting F.

The following information applies to 400 line FFT analyzers:

– with full scale frequency 1 kHz, a single spectrum approximates time weighting F;
– with full scale frequency 2 kHz or higher, the exponential average of two spectra approximates time weighting F. The full scale frequency shall not exceed the real time frequency of the analyzer.

With the WTGS stopped, the background noise shall be measured in the same way, and during similar wind conditions, as the WTGS noise measurements. The background noise shall only be integrated over a period of 2 min; measurements with time weighting F are not needed.

In cases where tonality changes with the wind speed, narrowband measurements shall be made at the wind speeds where the tones are most noticeable. This may be at wind speeds either higher or lower than the acoustic reference wind speed.

4.2.2.4 Optional measurements

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

Such a character might be the emission of infrasound, low-frequency noise, low-frequency modulation of the 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, at present, universally accepted and are given for guidance only.

4.2.3 Acoustic measurements at positions 2, 3 and 4

To fully characterize the acoustic emissions of a WTGS, the following acoustic measurements shall be made at positions 2, 3, and 4.

4.2.3.1 A-weighted sound pressure level

The equivalent continuous A-weighted sound pressure level of the noise from the WTGS shall be measured in the non-reference positions 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. Periods with intruding intermittent background noise shall be omitted. During the measurements, the wind speed averaged over each of the five periods shall differ by less than 2 m/s from the acoustic reference wind speed.

With the WTGS stopped, the background noise shall be measured immediately before or after each measurement of WTGS noise, using the same measurement setup, and under similar wind conditions. The 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 WTGS 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 the acoustic reference wind speed, and at least 25 % of the measurements shall be above and 25 % below the acoustic reference wind speed. Periods with intermittent background noise shall be omitted.

With the WTGS stopped, the background noise shall be measured immediately before or after the WTGS noise measurements in the same positions, using the same measurement setup, and during similar wind and background conditions. At least 10 measurements, each energy-averaged over at least 1 min, shall be obtained.

4.2.3.2 Octave, third-octave and narrow-band measurements

If the directivity of the WTGS noise is greater than 1,5 dB in any of the non-reference positions, the noise from the WTGS, measured in the position with the highest directivity, shall be measured and analyzed in narrow-band and octave or third-octave bands.

4.3 Non-acoustic measurements

The following non-acoustic measurements shall be made.

4.3.1 Wind speed measurements

The wind speed shall be determined according to one of the following two methods. Method 1 is the preferred method.

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

The wind speed shall be obtained from measurements of the electric power produced and preferably measured according to IEC 61400-12 from a traceable measured power versus wind speed curve, preferably for the same turbine or, otherwise, for the same type of wind turbine with the same components and adjustments.

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

The power curve relates the power to the wind speed averaged over the rotor swept area. For most WTGS, 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 use of power measurements and the WTGS power curve is the preferred method of wind speed determination, provided the WTGS operates below the maximum power point during the noise measurement series.

Record the power produced by the WTGS, and confirm that, for each noise sampling period, the power did not exceed 95 % of the maximum power point.

The power curve gives the relation between the wind speed at rotor centre height and the electric power that the turbine produces for standard atmospheric conditions of 15 °C and 101,3 kPa. The electric power measured during the noise measurements shall be converted to these 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 normalized 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 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 adjusted for a height of 10 m and the reference roughness length, as described in clause 5.

4.3.1.2 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 clause 5.

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

Wind speed data points shall be arithmetically averaged over the same period as, and shall be taken simultaneously with, the noise measurements.

4.3.2 Wind direction

Wind direction shall be observed from a wind direction transducer to ensure that measurement locations are within 15° of their nominal 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.

4.3.3 Other atmospheric conditions

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

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

5 Data reduction procedures

5.1 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:

$$V_s = V_z \left[\frac{\ln \frac{z_{ref}}{z_{0ref}} \ln \frac{H}{z_0}}{\ln \frac{H}{z_{0ref}} \ln \frac{z}{z_0}} \right] \qquad (5)$$

where

V_s is the standardized wind speed;

V_z is the wind speed measured at anemometer height z;

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 (5) 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 2.

Table 2 – Roughness length

Type of terrain	Roughness length z_0
Water, snow or sand surfaces	0,001 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

5.2 Correction for background noise

Using the methods specified in the relevant following paragraphs 5.3 to 5.7, 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 WTGS and background, the corrected value can be obtained using the following equation:

$$L_S = 10 \lg \left[10^{\left(0{,}1\, L_{s+n}\right)} - 10^{\left(0{,}1\, L_n\right)} \right] \qquad (6)$$

where

L_S is the equivalent continuous sound pressure level, in decibels, of the WTGS operating alone;

L_{s+n} is the equivalent continuous sound pressure level, in decibels, of the WTGS plus background; and

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

If the equivalent continuous sound pressure level of the WTGS plus background noise 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 WTGS noise was less than the background noise.

5.3 Apparent sound power level

A linear regression analysis shall be made with the 10 or more data pairs of equivalent continuous sound pressure level at the reference position and the wind speed, covering wind speeds differing less than 2 m/s from the acoustic reference wind speed. From this analysis the value of L_{Aeq} at the reference wind speed shall be determined.

A similar linear regression analysis, using at least 10 data pairs of the background noise measurements, shall be made. The value of L_{Aeq} at the acoustic reference wind speed shall be corrected for the background noise at the acoustic reference wind speed and shall be identified as $L_{Aeq,c}$.

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

$$L_{WA} = L_{Aeq,c} - 6 + 10\ \lg\left[\frac{4\pi R_1^2}{S_0}\right] \tag{7}$$

where

$L_{Aeq,c}$ is the background corrected A-weighted sound pressure level at the acoustic reference wind speed 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 (7) accounts for the approximate pressure doubling that occurs for the sound level measurements on a ground board.

5.4 Wind speed dependence

All of the more than 30 data pairs of wind speed and A-weighted equivalent sound pressure levels measured at the reference position shall be sorted into wind speed classes (bins). These classes shall be 1 m/s wide, non-overlapping and centred at integer values of the wind speed at the reference conditions. The arithmetic average of the wind speeds and the energy average of the noise levels shall be calculated in each class. If a class contains fewer than three data pairs, the averages shall be regarded as estimates, and shall be identified with the symbol "*".

A similar analysis shall be made of the background noise/wind speed data measured immediately before or after the WTGS noise measurements, but when the wind turbine is parked. The averages of the wind speeds in each class of the background noise measurements will, in general, differ from the corresponding averages of the WTGS noise measurements. Estimates of the background noise at the wind speeds corresponding to the class averages of the WTGS measurements shall be found by interpolation between neighbouring classes of background measurements. The result of the background noise at the wind speed thus determined shall be used for background noise correction.

Each average value of WTGS noise shall then be corrected for the corresponding value of background noise. The corrected average values are then normalised by subtraction of $L_{Aeq,c}$ at the acoustic reference wind speed.

As an alternative, if the data points have an apparent linear dependence, a linear regression analysis (least squares method; best linear fit) shall be made between the data pairs, and a similar linear regression analysis shall be made of the corresponding background noise measurement data points.

The expected levels from the linear regression analysis of the combined WTGS and background noise, and of the background noise, are found at all integer values of wind speed covered by the measurements. The levels of combined WTGS and background noise are corrected for the background level. These levels are then normalised by subtracting the corrected value at 8 m/s.

5.5 Directivity

The directivity of the WTGS noise in the directions of the three positions 2, 3, and 4 shall 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:

$$\Delta_i = L_{Aeq,i} - L_{Aeq,1} + 20 \lg (R_i / R_1) \quad (8)$$

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 WTGS 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 WTGS noise measurements shall be corrected for background noise and the directivity Δ_i at each position determined using equation (8).

5.6 Octave or third-octave band levels

The octave or third-octave band levels of the WTGS noise shall be corrected for the corresponding octave or third-octave band levels of the background noise.

5.7 Tonality

The presence of tones in the noise shall be determined on the basis of the narrow-band analysis as follows:

– the sound pressure level of the tone shall be determined;

– the sound pressure level of the broadband masking noise in a critical band about the tone shall be determined;

– the difference ΔL_{tn} between the sound pressure level of the tone and the masking noise level shall be found.

If the WTGS has several widely spaced tones, the difference ΔL_{tn} shall be determined for each critical band. Tones for which ΔL_{tn} is below the value as calculated from equation (9) may be neglected.

$$\Delta L_{tn} = -2 - \lg \left[1 + \left(\frac{f}{502} \right)^{2,5} \right] \quad (9)$$

where

f is the frequency of the tone, in hertz.

The bandwidths of the critical bands are:

Table 3 – Bandwidth of critical bands

Centre frequency f_c, Hz	**Below 500**	**Above 500**
Bandwidth	100 Hz	20 % of f_c

The critical band shall be positioned with centre frequency coincident with the tone frequency. If more than one tone is present within the same critical band, the critical band shall be placed so that ΔL_{tn} is maximized. For tones with frequencies between 20 Hz and 70 Hz the critical band is 20 Hz to 120 Hz.

The sound pressure level of the tone shall be read from the frequency analysis. If more tones are present within the same critical band, the overall tone level L_{pt} is determined by energy-summing the level of each individual tone within the critical band.

The tone level shall be determined from the analysis with time weighting F as the arithmetic average of the highest 25 % of the tone levels.

The sound pressure level of the masking noise shall be obtained from the long-term spectrum-averaged over the same time period as the tone level. All spectral peaks resulting from the tones and their possible sidebands shall be disregarded. The total masking noise level within the critical band L_{pn} corrected for the bandwidth of the critical band, is determined by:

$$L_{pn} = L_{pn,avg} + 10 \lg \left[\frac{\text{critical bandwidth}}{\text{effective noise bandwidth}} \right] \qquad (10)$$

where

$L_{pn,avg}$ is the energy averaged measured masking noise level obtained from the narrowband analysis, and determined by averaging the masking noise spectrum separate from any tones within the critical band.

A narrowband analysis shall be made of the background noise for comparison with the corresponding analysis of the WTGS noise. It must be ensured that the tones do not originate from the background noise. L_{pn} shall be corrected according to equation (6), using the level of the background noise in the same critical band as used during the tone analysis. The background noise shall be at least 6 dB lower than the WTGS noise in the relevant critical bands. If this is not the case, a statement shall be recorded that the masking noise is influenced by background noise.

The difference between the tone level and the level of the masking noise in the corresponding critical band, is given by:

$$\Delta L_{tn,max} = L_{pt} - L_{pn} \qquad (11)$$

Additionally, in some occasions, tonal content may be described using the tone level as well as the noise level read from the long-time narrowband analysis. This will in general differ from the tonality defined above using the average maximum tone level. The long-time averaged tonal content shall be described by a symbol $\Delta L_{tn,ave}$.

6 Information to be reported

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

6.1 Characterization of the wind turbine

The wind turbine configuration shall include the following information :

– Wind turbine details:
  - manufacturer;
  - model number;
  - serial number.
– The configuration:
  - vertical or horizontal axis wind turbine;
  - upwind or downwind rotor;
  - rotor centre height;
  - horizontal distance from rotor centre to tower axis;
  - diameter of rotor.
– Operating details:
  - stall or pitch controlled turbine;
  - power curve (if required for wind speed determination);
  - fixed or variable pitch.

The following are other items that may affect the acoustic performance and, if their configuration is not defined by the model number reported, they should also be declared by the manufacturer and reported:

– The geometric configuration:
  - tower type (lattice or tube);
  - tower height.
– Rotor details:
  - rotor control devices;
  - blade type;
  - number of blades.
– Operating details:
  - rotational speed at reference wind speed and at rated power;
  - pitch angle;
  - rated power output.
– Gearbox details:
  - manufacturer;
  - model number.
– Generator details:
  - manufacturer;
  - model number;
  - rated power output;
  - rotational speed.

6.2 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 m);

– 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.

6.3 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);

– microphone mounting board dimensions;

– anemometer position and measured height for each measurement series.

6.4 Acoustic data

To the extent that they are included in the actual measurements, the following acoustic data shall be reported:

– the measured position of each microphone for each measurement series;

– L_{WA} , and indication of the wind speed determination method;

– a plot showing all measured data pairs at position 1 of the WTGS 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;

– dependence of the sound level upon wind speed as a table and a graph of background corrected normalised values. The axes of the graph shall be linear, and scaled so that 1 m/s corresponds to 2 dB;

– directivity Δ_i for each of positions 2, 3, and 4, and corresponding wind speeds averaged over the periods in which the directivity is measured;

– table and plot of sound pressure spectrum in full or third octaves; co-ordinates plotted at 1 octave = 10 dB, and marked with an asterisk as appropriate;

– tonality ($\Delta L_{tn,max}$ and the frequency of the tones) and masking noise, if influenced by background;

– time and date of each measurement series;

– any other acoustic measurements, including calibration data.

6.5 Non-acoustic data

The following non-acoustic data shall be reported:

- 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.

6.6 Uncertainty

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

- the apparent sound power level;
- the wind speed dependence of the A-weighted sound pressure level at the reference position;
- the directivity at the acoustic reference wind speed;
- the octave or third-octave band spectrum of the noise at the reference position at the acoustic reference wind speed;
- the tonality of the sound emissions of the WTGS measured at the reference position.

Guidance for the assessment of measurement uncertainty can be found in annex D and in [1]* .

* The figure in square brackets refers to the bibliography.

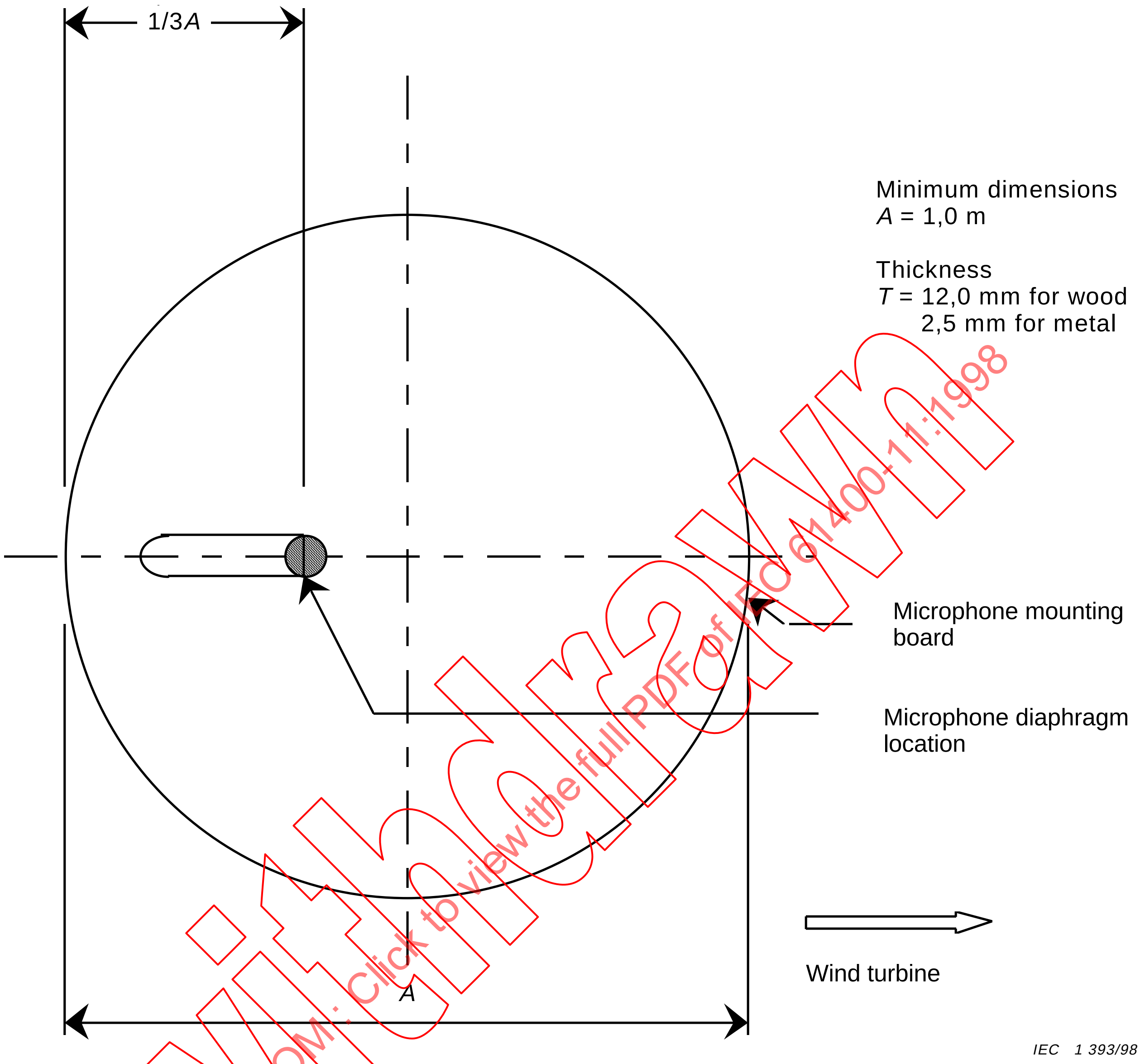

Figure 1 – Mounting of the microphone – plan view

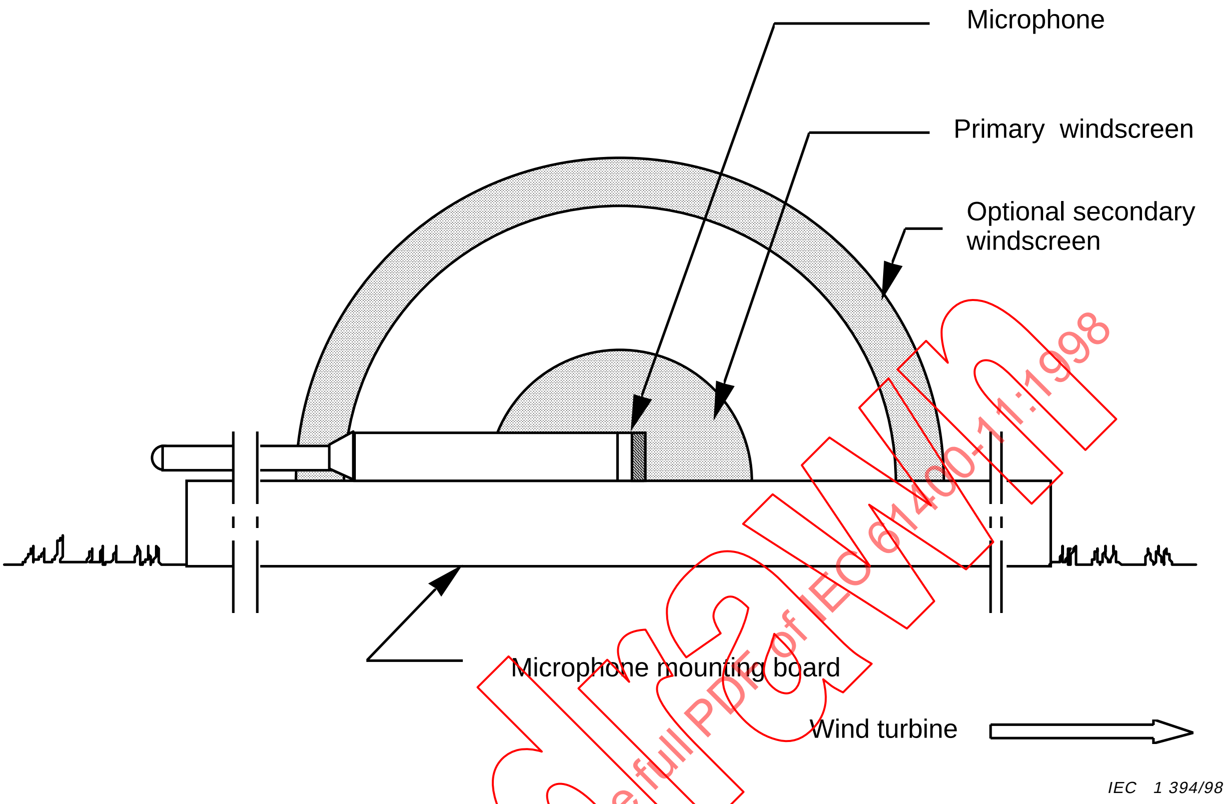

Figure 2 – Mounting of the microphone – vertical cross-section

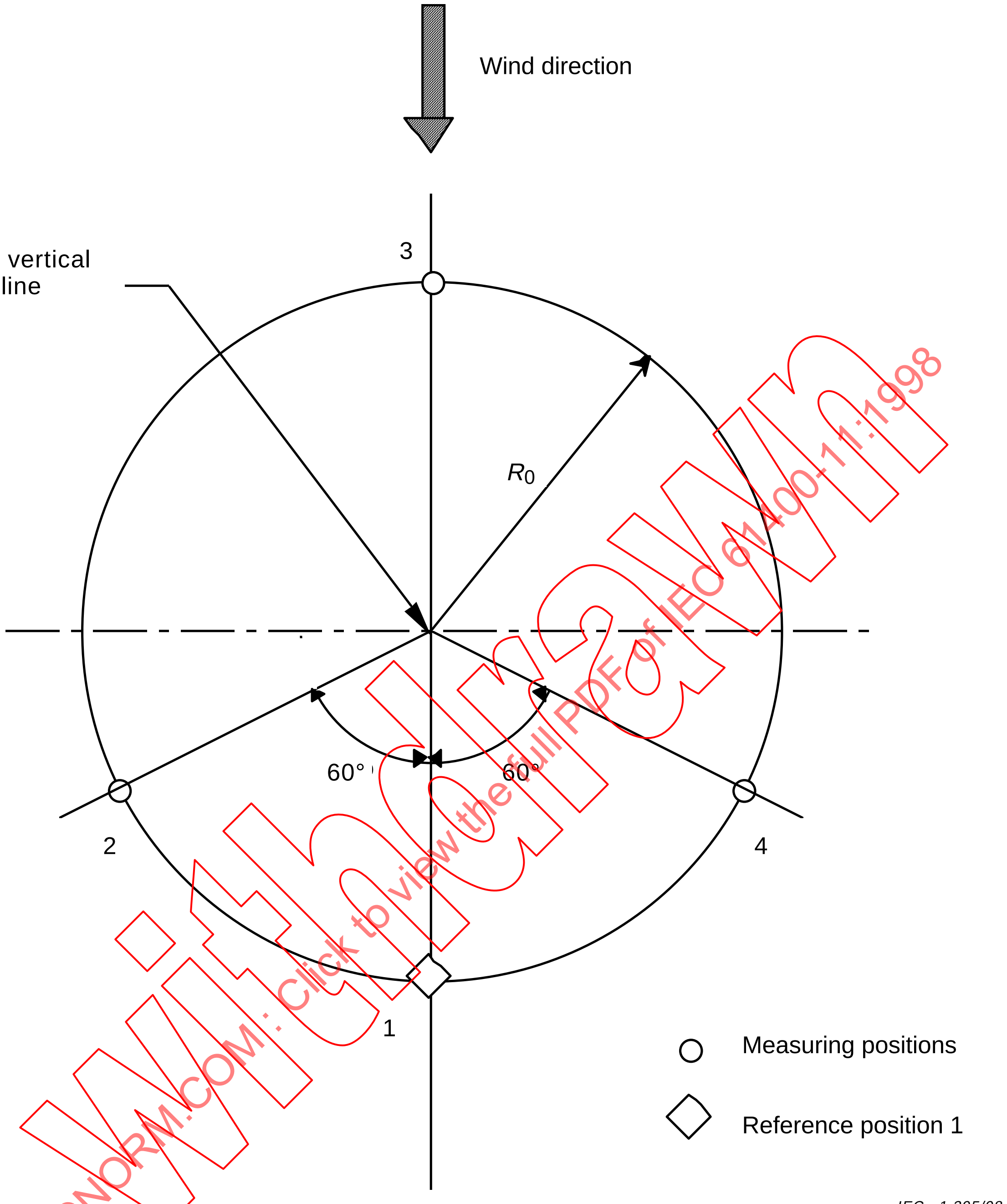

Figure 3 – Standard pattern for microphone measurement position (plan view)

Figure 4a – Horizontal axis turbine

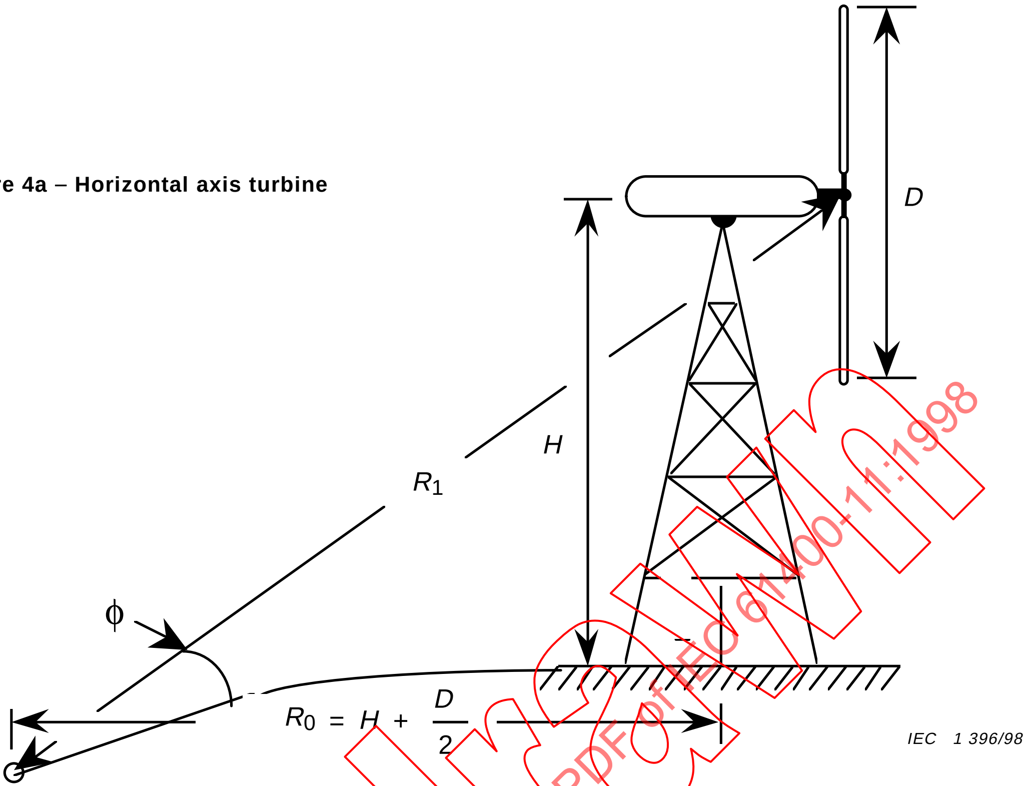

Figure 4b – Vertical axis turbine

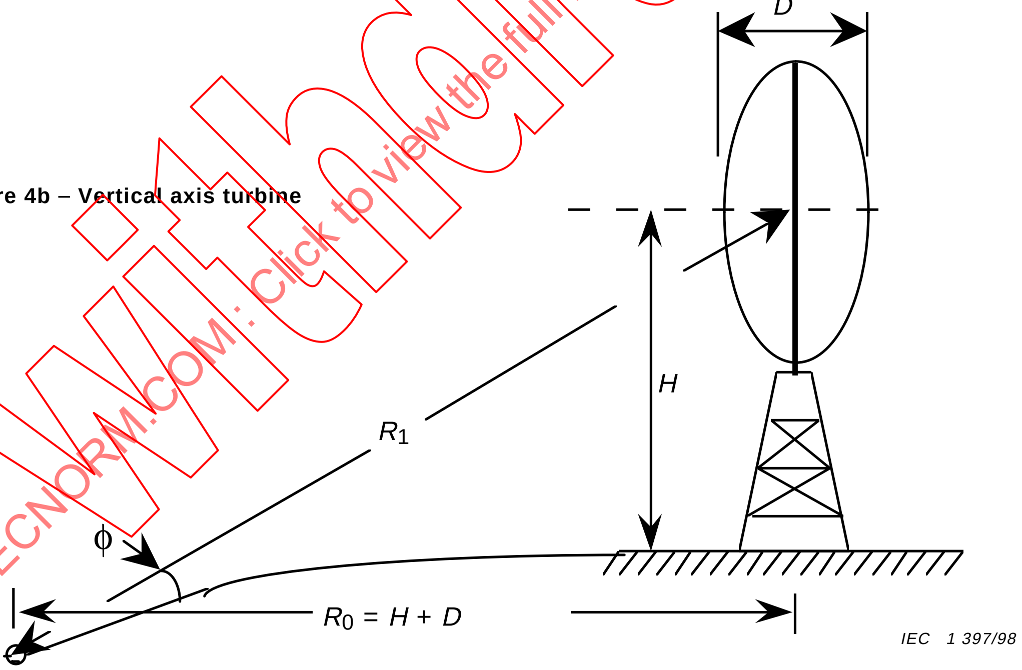

Figure 4 – Illustration of the definitions of R_0 and slant distance R_1

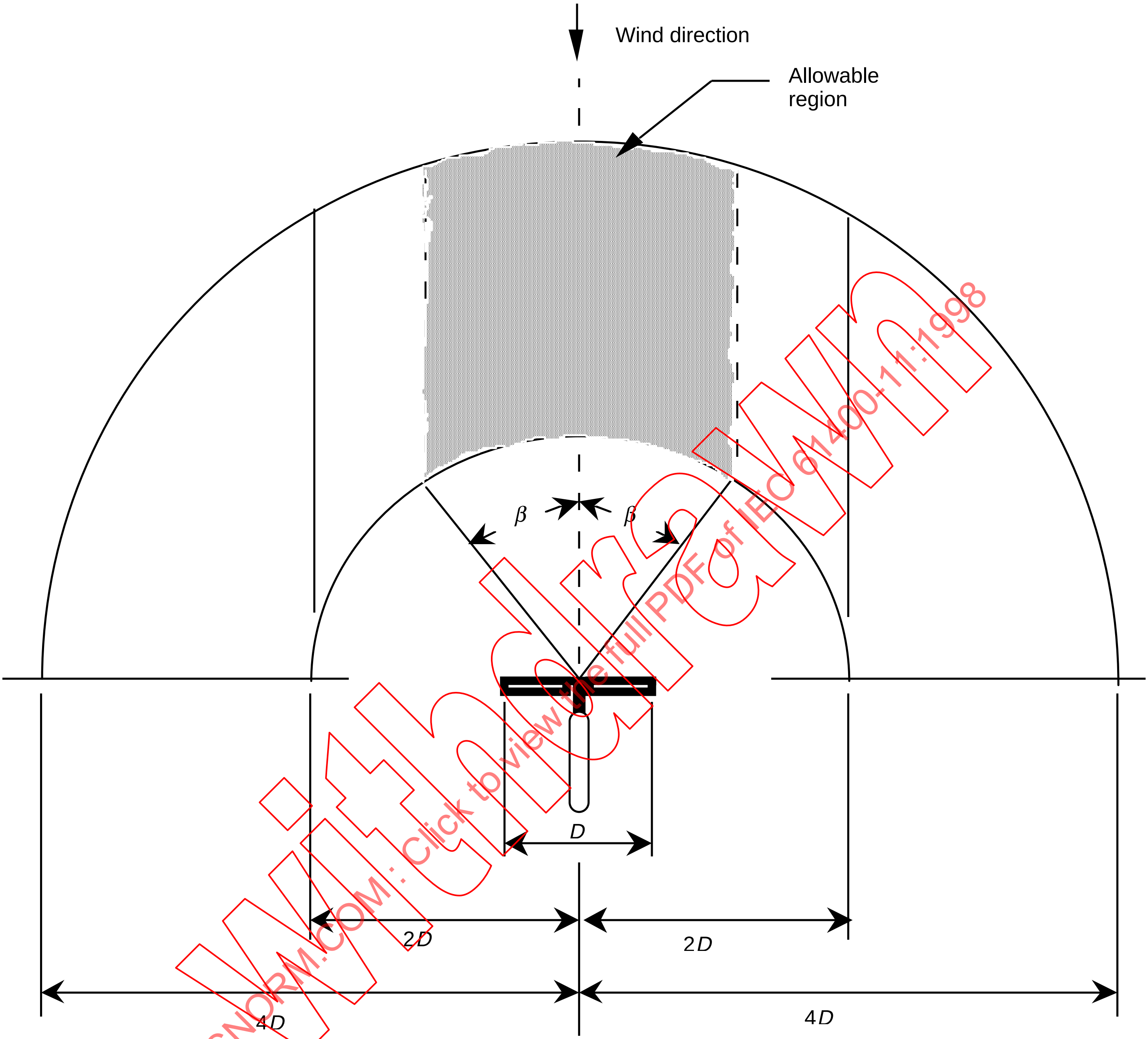

Figure 5 – Allowable region for meteorological mast position as a function of β – plan view – (ref. 4.1.2)

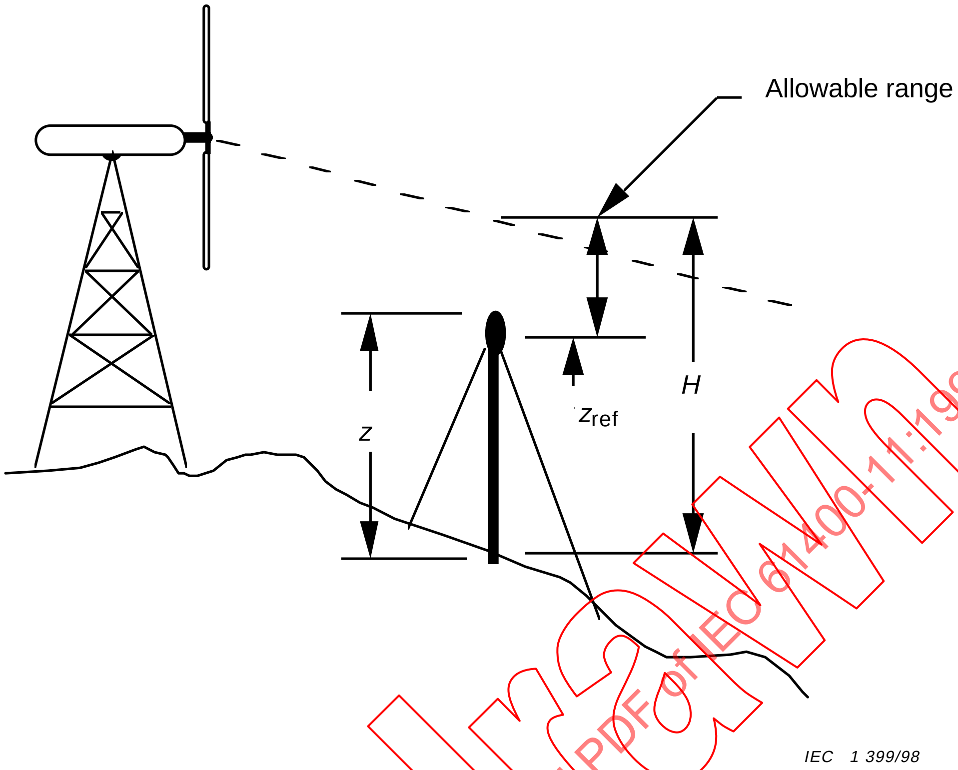

Figure 6 – Allowable range for meteorological mast position – cross-section – (ref. 4.1.2)

Annex A
(informative)

Other possible characteristics of WTGS noise emission and their quantification

A.1 General

In addition to those characteristics of WTGS 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 WTGS 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 [2]*.

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 characterized 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 octave or third-octave band measurements described in the main body of the text, down to 20 Hz. For octave bands, the 31,5 Hz octave band should additionally be determined, and for 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.

* The figure in square brackets refers to the bibliography.

A.4 Impulsivity

An impulsive, thumping sound may be emitted from a WTGS due, for example, to the interaction of the blade with the disturbed wind around the tower. Impulsivity is a measure of the degree of this thumping.

A quantification of impulsivity can be obtained from the average of several measurements of the difference between the C-weighted "impulse hold" and maximum C-weighted "slow" sound pressure levels.

The impulsive character can also be displayed by recording the filtered sound pressure signal using a 31,5 Hz octave band filter.

A.5 Amplitude modulation of the broadband noise

In some cases, it is possible that the broadband noise emitted by a WTGS is modulated by the blade passage frequency giving rise to a characteristic "swishing" or "whooshing" sound.

This modulation can be displayed by recording the measured A-weighted sound pressure level with time weighting F for at least 10 blade passes by the turbine.

The characteristics of this modulation can be influenced by local atmospheric conditions (see annex C), and for this reason such conditions should be recorded during measurements.

A.6 Other noise characteristics

If the noise emission contains a whine, hiss, screech, hum, bang, clatter, click, thump, etc., then this characteristic should be reported. As full a description as possible of the noise should be given in words, and any measurements that illustrate the nature of the noise should be taken.

Annex B
(informative)

Criteria for recording/playback equipment

B.1 General

A chain of instruments may consist of: microphone; sound level meter; recorder (record/playback); and analyzer. As a guideline, typical requirements are presented for tape recorders.

B.2 Analogue tape recorders

For analogue tape recorders:

– the record/playback frequency characteristic at a recorded level 20 dB below the reference level (reference level: 405 pico Weber per millimetre track width) should be within the tolerances of IEC 60651 for type 1 sound level meter from 30 Hz to 10 kHz. These tolerances are illustrated below. It is appropriate to specify tighter tolerances in the range 10 Hz to 20 Hz, (that is ±3 dB) if low frequency measurements are made;

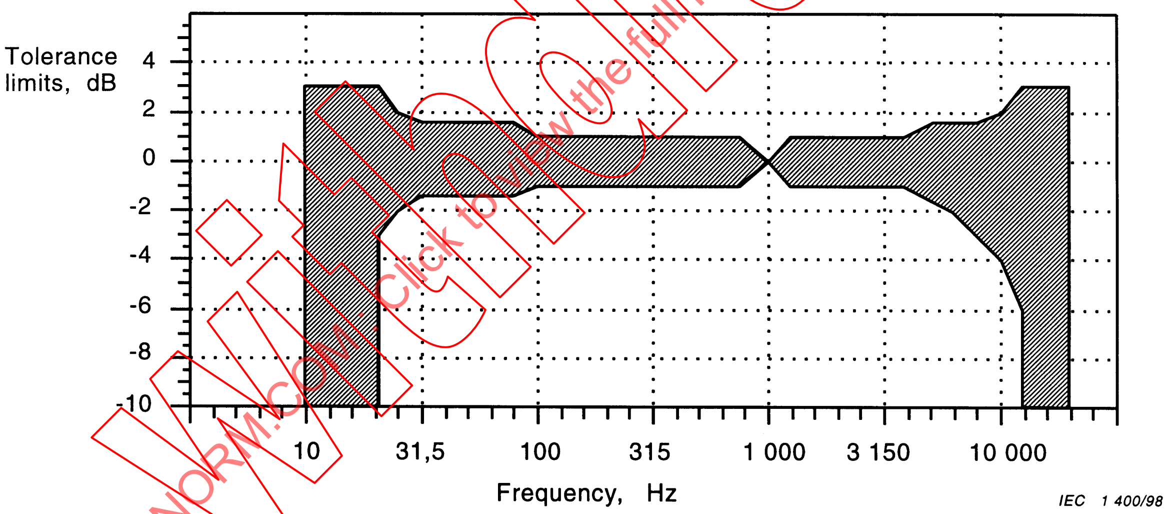

Figure B.1 – Tolerances for frequency characteristics, IEC 60651 type 1

– with a recorded 1 kHz tone at the reference level, the third harmonic distortion should not exceed 3 %;

– the playback noise should not exceed:
  - 60 dB below the reference level (A-weighted);
  - 50 dB below the reference level (linear, 30 Hz to 10 kHz);

– the crosstalk attenuation at 1 kHz should exceed 50 dB;

– the weighted peak value of wow and flutter according to IEC 60386 should not exceed 0,3 %.

B.3 Digital tape recorders

For digital tape recorders:

– the record/playback frequency characteristic at maximum level (0 dB) and –20 dB, –40 dB and –60 dB should be 30 Hz to 10 kHz with the tolerances of IEC 60651 for type 1 sound level meter;
– the level linearity measured at least with the tone frequencies 31,5 Hz, 1 kHz and 8 kHz should keep within the IEC 60651 tolerances at least in the range from maximum level (0 dB) to –60 dB. These tolerances are ±0,7 dB relative to the reference level (–20 dB) and ±0,4 dB for any 5 dB or 10 dB level shift.
– the signal-to-noise ratio should exceed:
  - 80 dB (A-weighted);
  - 75 dB (flat, 30 Hz to 10 kHz).