EXPERT GROUP STUDY

ON

RECOMMENDED PRACTICES FOR WIND TURBINE TESTING AND EVALUATION

10. MEASUREMENT OF NOISE IMMISSION FROM WIND TURBINES AT NOISE RECEPTOR LOCATIONS

Submitted to the Executive Committee
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for
Research and Development
on Wind Energy Conversion Systems

RECOMMENDED PRACTICES
FOR WIND TURBINE TESTING

10. MEASUREMENT OF NOISE IMMISSION FROM WIND TURBINES AT NOISE RECEPTOR LOCATIONS

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FOREWORD

This guide recommends measurement techniques and methods which will enable a characterisation of the noise immission from a wind turbine or a group of wind turbines at a noise receptor location. It complements a previous document dealing with the measurement of the source strength of a wind turbine, Reference [1].

In several countries standards or guidelines on how to measure noise immission from industrial sources have been implemented. However, it is, in general, not possible to apply the procedures specified in these documents to wind turbine acoustic measurements since they must be carried out in windy conditions outside the scope of the standards dealing with noise from industrial plants.

This guide provides several practical and reliable methods for determining wind turbine noise immission: three methods for equivalent continuous *A*-weighted sound pressure levels and one method for *A*-weighted percentiles. Special importance is attached to the problem of correcting for background noise and techniques for improving the signal-to-noise ratio.

Contents

1. PURPOSE

The purpose of this guide is to provide a set of techniques and methods for the measurement and description of wind turbine noise immission, that is, wind turbine noise at receptor locations.

These techniques and methods have been prepared so that they can be used by

- manufacturers,
- developers,
- operators,
- planning authorities,
- research and development engineers,

for the purpose of verification of compliance with noise immission limits and of noise propagation models.

The measurement of noise immission from wind turbines is a complex acoustic task. This guideline cannot cover all possible problems that may be encountered on, for instance,
- determination of wind speed,
- measurements in cases of low signal-to-noise ratio,
- allowance for reflections from buildings.

Thus, it is strongly recommended that the measurements described in this guide are always carried out by experienced acousticians.

2. SCOPE

This guide primarily provides information on the instrumentation, measurement methods and data reduction methods which are required to determine the noise immission from a single wind turbine or a group of wind turbines. There is no restriction to the type or the size of the machines although the guideline only applies to wind turbines.

Measurements can, according to this guide, be carried out in all directions around a wind turbine or group of wind turbines. The noise immission is described either by its equivalent continuous *A*-weighted sound pressure level or *A*-weighted percentiles, in both cases together with narrow band spectra if required. As many national guidelines, in order to improve the measurement reproducibility, recommend that the measurements be taken during special propagation conditions, that case is treated in some detail in an appendix.

The document does not address the psycho-acoustic aspects, nor does it attempt to define acoustic limits of acceptability for regulatory purposes.

3. DEFINITIONS

3.1 A-weighted sound pressure level, L_{pA}, in decibels

The value of the sound pressure level determined using frequency-weighting characteristic A (see IEC Publication 651, Reference [2]). The reference sound pressure is 20 μPa. The A-weighted sound pressure level is, in this document, also referred to as the 'sound level'.

3.2 Equivalent continuous A-weighted sound pressure level, $L_{Aeq,T}$, in decibels

Value of the A-weighted sound pressure level of a continuous, steady sound that, within a specified time interval T, has the same mean square sound pressure as a sound under consideration whose level varies with time. It is given by the formula

$$L_{Aeq,T} = 10 lg\left(\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} \frac{p_A^2(t)}{p_0^2} dt\right), \qquad (1)$$

where $L_{Aeq,T}$ is the equivalent continuous A-weighted sound pressure level, in decibels, determined over a time interval T starting at t_1 and ending at t_2,
p_0 is the reference sound pressure, 20 μPa,
$p_A(t)$ is the instantaneous A-weighted sound pressure of the sound signal.

3.3 A-weighted percentiles, L_{Ax}, in decibels

The quantity L_{Ax} is defined as the value of the A-weighted sound pressure level that over a specified reference time is exceeded x per cent of the time. The percentiles L_{A10}, L_{A90} and L_{A95} are often used. In this document, the reference time period is specified as 10 minutes and the time weighting characteristic as 'F', see Reference [2].

3.4 Tonality

The difference between the level of one or several tones and the masking noise in the critical band centred around the tone(s), see clause 8.8.4.

3.5 Ambient sound

The existing environmental sound excluding the noise from the wind turbine(s) under consideration.

3.6 Background noise

Background noise is the total of all sources of interference at the time of noise measurements. Thus, ambient sound constitutes part of the background noise. Other sources can be noise generated by wind at the microphone diaphragm, electric noise in the instrumentation, etc.

3.7 Target wind speed

The wind speed at which it is desired to determine the noise immission. The target wind speed is usually related to the conditions at the turbine site and can be defined as the wind speed at a height of 10 m or at the hub height.

The target wind speed is usually set by regulatory authorities. In the absence of such information, it is recommended that the target wind speed be defined as the wind speed of 8 m/s at the turbine site and at a height of 10 m.

3.8 Preferred propagation conditions for improved measurement reproducibility

The preferred propagation conditions for improved measurement reproducibility are defined in the following way:

- the wind speed should be equal to the target wind speed,
- the wind direction should be within $\pm 45^{o}$ of the direction from the wind turbine to the receptor (in the case of a group of turbines, this condition refers to the turbine which dominates the receptor noise immission level),
- the vertical temperature gradient dT/dz should be in the interval $-0.05\ ^{o}C/m < dT/dz < 0.05\ ^{o}C/m$).

A discussion on these conditions can be found in Appendix 2.

4. INSTRUMENTATION

4.1 Acoustic instruments

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

This equipment should meet the requirements of a type 1 sound level meter according to IEC Publication 804, Reference [3]. The diameter of the microphone should not exceed 13 mm.

4.1.2 Equipment for the determination of A-weighted percentiles

In addition to the requirements for sound level meters and microphones given in clause 4.1.1, the equipment should be capable of providing a read-out of, or otherwise have the facility to obtain the A-weighted percentiles wanted for the measurement under consideration. The time weighting should be 'F' according to IEC 651 (Reference [2]) and the reference time period 10 minutes. If no other information is available, the equipment should be suitable for the determination of the percentiles L_{A10}, L_{A90} and L_{A95}.

4.1.3 Equipment for the determination of narrow band spectra

In addition to the requirements for sound level meters and microphones given in clause 4.1.1, the equipment should have a substantially constant frequency response from 45 Hz up to 5600 Hz. FFT analysers should have a resolution of at least 400 lines and a real time upper limiting frequency of 5 kHz. It should be possible to choose the following frequency resolution:

Tone frequency, Hz	Resolution, Hz
< 2000	2.0 - 5.0
≥ 2000	2.0 - 12.5

It should be possible to analyse with a time weighting which approximates the standard time weighting characteristic 'F', see clause 7.3.

4.1.4 Calibrator

The acoustic calibrator should have an accuracy equal to or better than ±0.3 dB (Class 1 according to IEC 942, Reference [4]) in the temperature range where it is used.

4.1.5 Recording of data

When data are recorded on tape as an essential part of the measuring procedure, the complete measurement/analysis chain should fulfil the requirements of IEC 651, type 1. Attention should be given to the dynamic range of the recorder: the signal-to-noise ratio should be at least 50 dB.

4.2 Windscreens

Depending on the purpose of the measurement and the conditions of the site, the microphone may be free-standing or mounted on a vertical measurement board.

The windscreen to be used together with a free-standing microphone should consist of a primary and, where necessary, a secondary windscreen. The primary windscreen should consist of an open cell foam windscreen with a diameter of approximately 90 mm, which is centred around the diaphragm of the microphone. The secondary windscreen should be used when necessary to obtain an improved signal-to-noise ratio at low frequencies, see Reference [5] and [6]. It could, for example, consist of a spherical wire frame, of 250 mm in diameter, covered with a 25 mm layer of open cell foam with a porosity of 4 to 8 pores per 10 mm. This secondary windscreen should also be centred around the diaphragm of the microphone. The frequency response of the microphone system must be documented.

Alternatively, the windshield design described in Reference [7] could be used. This is particularly suitable if octave band measurements are otherwise unnecessary.

When the microphone is mounted on a vertical measurement board, one half of the primary and, where necessary, one half of the secondary windscreen described above should be used. The two hemi-spherical windscreens should be centred around the diaphragm of the microphone and rigidly mounted on the board.

4.3 Measurement boards

Two types of vertical boards can be used, one of which is termed large and the other small. The large one is used for measurements far away from buildings in cases of low signal-to-noise ratio. The small one is used for measurements on building facades in order to obtain a well defined reflecting surface.

4.3.1 The large measurement board

The board should be rectangular with the minimum dimensions 1.5 m x 1.8 m. It should be flat and made from a material that is acoustically hard, e.g. a piece of plywood or hard chip-board with a thickness of at least 12 mm. The board should be placed with the two longer sides parallel to the ground. The recommended microphone positions are shown in Figure 1.

The microphone should be mounted with the microphone diaphragm flush with the face of the board, see Figure 2.

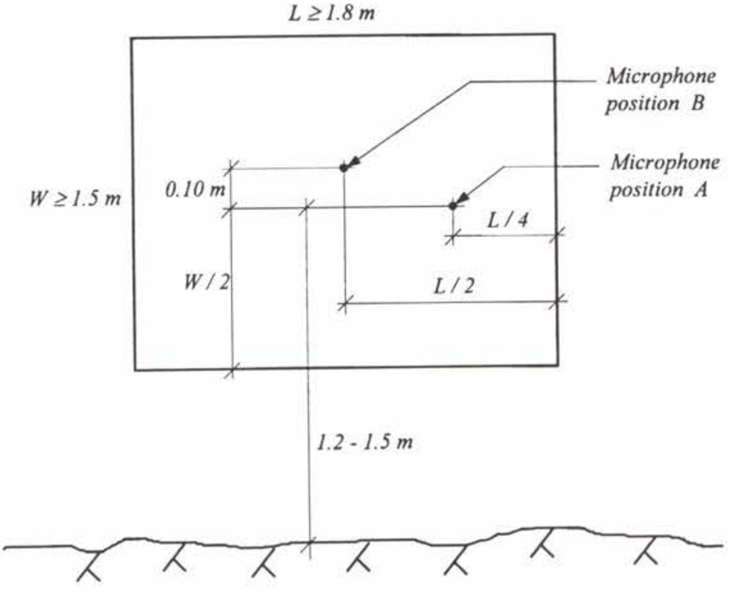


Figure 1. Position of microphone on the large measurement board. Front view. Microphone position A is recommended when the board is used to reduce the influence from sources shielded by the board or reflections from surfaces shielded by the board. Microphone position B is recommended when the board is used to reduce the wind induced microphone noise.

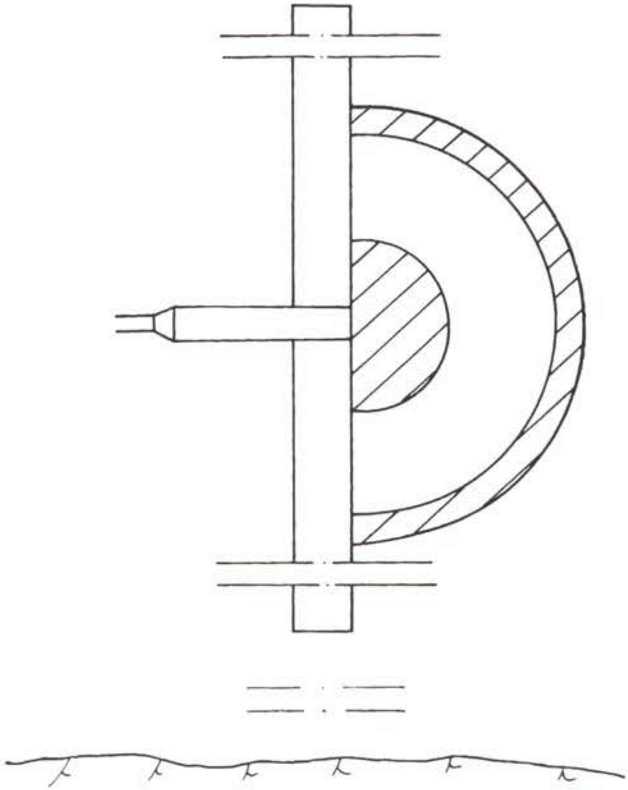


Figure 2. Mounting of microphone on the large measurement board. Vertical cut (not to scale).

4.3.2 The small measurement board

The dimensions of the board should be at least 0.5 m x 0.7 m. The board should be flat and made from a material that is acoustically hard, e.g. a piece of plywood or hard chip-board with a thickness of at least 12 mm but not more than 30 mm.

When the microphone is mounted on the board, the distance between the centre of the microphone diaphragm and the surface of the board should not exceed 8 mm. The microphone diaphragm should be located at least 100 mm from the edges and symmetry lines of the board, see Figure 3, and mounted in the vertical direction with the diaphragm below the pre-amplifier as shown in Figure 4.

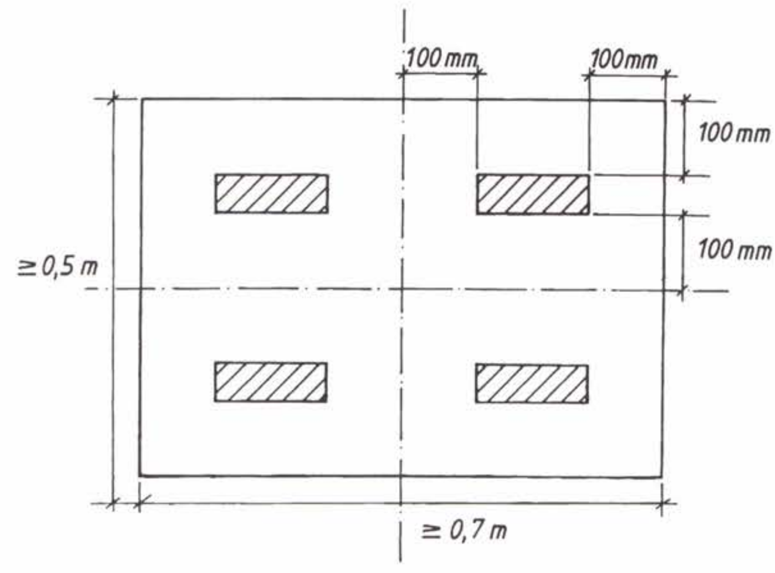


Figure 3. Recommended positions on the small board for the microphone diaphragm.

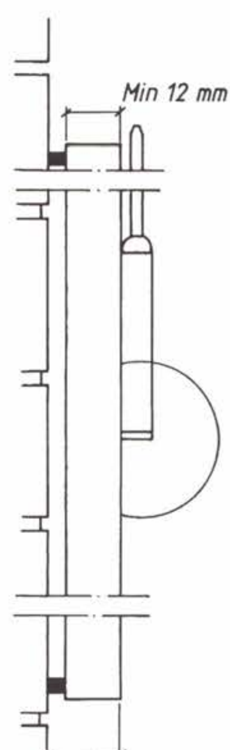


Figure 4. Mounting of the small board on a facade.

4.4 Non-acoustic measurement equipment

4.4.1 Wind speed

Anemometers should have an accuracy equal to or better than ±0.2 m/s in the wind speed interval 4 - 12 m/s.

However, anemometers used only for background noise corrections may have an accuracy equal to or better than ±0.4 m/s in the wind speed range 4 - 12 m/s.

4.4.2 Wind direction

The wind direction transducer should have an accuracy equal to or better than $\pm 5^{o}$.

4.4.3 Temperature

The temperature should be determined with a shielded thermometer or other temperature sensor. The device should be accurate within $\pm 1\ ^{o}C$ over the temperature range experienced during the measurements.

4.4.4 Local atmospheric pressure

A barometer should be used for the determination of local atmospheric pressure. It should have an accuracy equal to or better than ±1 kPa over the range of pressures experienced during the measurements.

4.4.5 Other equipment

Equipment used to measure heights and distances should provide an accuracy within ±2%.

Equipment used for angular measurements should have an accuracy equal to or better than $\pm 5^{o}$.

4.5 Calibration and verification

The complete acoustic measurement chain should be calibrated at least at one frequency before and after the measurements. As a minimum the following equipment should be checked regularly and be calibrated with traceability to a primary calibration laboratory. The maximum time from the latest calibration of this type should not exceed
- Acoustic calibrator: 12 months,
- Microphone: 24 months,
- Integrating sound level meter: 24 months,
- Spectrum analyser: 36 months,
- Data recording/playback system: 24 months,
- Wind speed meter: 12 months.

5. MEASUREMENT OF EQUIVALENT CONTINUOUS A-WEIGHTED SOUND PRESSURE LEVELS

According to this guide, broadband noise from wind turbine(s) and background sources can be described by either the equivalent continuous A-weighted sound pressure level, $L_{Aeq,T}$, or by one or several A-weighted percentiles L_{Ax}. The measurement technique for $L_{Aeq,T}$ is described in this chapter and the technique for L_{Ax} in chapter 6.

5.1 Outline of the methods

A major problem when measuring noise immission from wind turbines is the influence of background noise generated by, for instance,
- the wind at the microphone,
- the wind acting on adjacent trees, shrubs and structures,
- traffic on nearby roads and rail tracks,
- aircraft and industries,
- animal and human activities,
- streams or waves on shorelines.

For $L_{Aeq,T}$ measurements it is assumed that the noise emitted by the turbine(s) is a function of the wind speed at the turbine site, and that the background noise is a function of the wind speed at the receptor site.

In many measurement situations, the sound level from a wind turbine is of the same order of magnitude as the background noise level. This implies that a very important task is to correct the measured levels for the influence of the background noise. However, situations also exist when it is sufficient to make a measurement of the combined level of the turbine sound and background noise. This is the case when, for instance, the purpose of the measurements is to verify that the level of the turbine noise is below a certain limit and the measured value of the combined noise from the turbine(s) and the background is below that limit.

For this reason, several types of measurement techniques with increasing complexity (and precision) are described in this guide. The techniques for $L_{Aeq,T}$ are given in this chapter and are summarized below.

Method A. Measurement of noise level from turbine(s) alone
In this measurement method the combined level from the turbine(s) and all other sources is measured simultaneously with the wind speed, obtained from an anemometer at the receptor location. Measurements are carried out at varying wind speeds. The turbine or turbines are then parked and the background noise is measured, again together with the wind speed. The noise level of the turbine(s) alone is determined from the measurement results.

The result can be used for a comparison of the noise level from the turbine or turbines with a specified limit, provided that this limit is not related to a certain wind speed at the wind turbine location.

Method B. Measurement of combined noise level at a target wind speed
In this method, the combined level of the turbine and background noise is measured at the receptor location. The wind speed is measured at the turbine site using either an anemometer or the electric output of the turbine in combination with the power curve. The wind speed is converted to a height of 10 m or to the hub height. The noise level is measured at varying wind speeds and

is plotted in a graph as a function of the converted wind speed. The data points are approximated with a straight line and the level at the target wind speed is read from the line.

The value obtained in this way should be regarded as an upper limit of the turbine noise at the target wind speed. It should be observed that the result from a measurement of this type can be used to demonstrate that the noise level from the turbine or turbines is lower than a specified limit but cannot be used to demonstrate that the noise level exceeds a limit.

At positions of interest for noise immission measurements, turbine noise levels can often be expected to be below but quite close to the specified immission limit. At the same time, the level of the background sound will often be of the same order of magnitude as the turbine noise level. This implies that the measured combined level will in many cases in practice be higher than the limit. As the results using this method can be used only if the combined level is below the specified limit, it is realised that the applicability of this method is limited.

<u>Method C. Measurement of noise level from turbine(s) alone at a target wind speed</u>
The combined noise from the wind turbine(s) and all other sources is measured at the receptor location simultaneously with the wind speed at two points: the turbine site and the receptor location. A set of data triplets are obtained at varying wind speeds. In a similar way, the background noise alone is measured with the turbine(s) parked and simultaneously with the wind speed at the receptor location. The two groups of noise levels are plotted in a graph as a function of the wind speed at the receptor location. The background noise levels are approximated with a curve (using a regression technique) and the levels of the turbine alone are determined for every one of the data points.

The wind speeds obtained at the turbine site are, if necessary, converted to the same height as that used for the target wind speed. The corrected noise levels of the turbine alone are then plotted as a function of the converted wind speed. The noise level points are approximated by a straight line and the level at the target wind speed is read from the line.

5.2 Noise measurement positions

The choice of positions for measurement of noise levels should be directed by the purpose of the measurement. However, the conditions of the site may also affect the choice of measuring positions and the microphone mounting technique to be used.

Measurements can be carried out with a free-standing micro-phone or a microphone mounted on a vertical board. The preferred method is to use a free-standing microphone at a height of either 1.2 - 1.5 m or 5.0 m. This type of micro-phone position can be used provided that the signal-to-noise ratio is high enough (at least 3 dB and preferably 6 dB or more, see clause 8.2) and the distance to all reflecting surfaces is large enough, see Appendix 1.

The use of two types of boards is described in this document.
A small board can be used for measurements upon building facades in order to obtain a well-defined reflecting surface. A large vertical board can be used to suppress background noise or noise reflected from adjacent vertical surfaces, see clause 5.2.3.

5.2.1 Free-field positions

If the purpose of the measurement is to determine the actual sound level at a specific point, the microphone should, of course, be placed at that point.

However, if the purpose of the measurement is to determine the noise level in absence of reflections from vertical surfaces, for instance building facades, the microphone position should be chosen so that the level of the sound reflected from nearby vertical surfaces is more than 6 dB below the level of the sound from the wind turbine, see Appendix 1 for more information. If this is not possible, the technique using a free-standing large measurement board or a small measurement board on a building facade should be used.

5.2.2 Positions on a building facade

A small board should be used and be placed on the outer side of a building facade and facing the wind turbine(s). The board is described in clause 4.3.2. The same microphone height as for a free-standing microphone should be used.

The board should be parallel with the facade. The distance between the microphone side of the board and the facade should not exceed 30 mm, see Figure 3. The normal to the face of the board should point towards the centerline of the wind turbine tower within $\pm 45^{o}$ (or, in the case of a group of turbines, to the tower of the turbine which gives the predominant contribution to the total sound level). The microphone should also be at least 0.75 m from the corners of the facade, open windows and major recesses, at least 1.0 m from the base of the roof and at least 1.2 m above the ground.

5.2.3 Positions using a large free-standing board

The board should be in the vertical direction (within $\pm 5^{o}$) and with the longer sides parallel to the ground. The normal to the face of the board should point towards the centerline of the tower of the wind turbine (or, in the case of a group of turbines, to the tower of the turbine which gives the predominant contribution to the total sound level). The microphone should be placed at a height of 1.2 - 1.5 m above the ground and face the wind turbine. In the case of a group of turbines, all the turbines in question must be situated in front of the board.

The advantages of using a large board are:

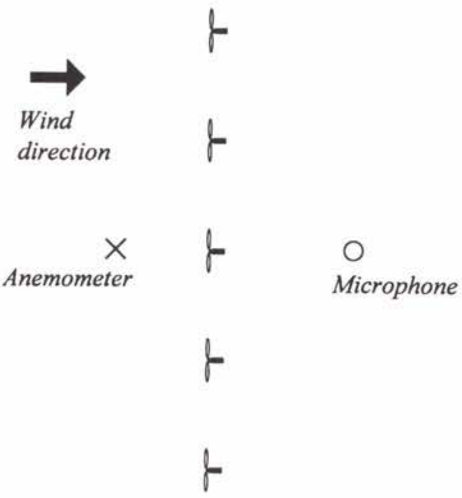
- a reduction of the influence of sound reflected from vertical surfaces behind the board,
- an improvement of the signal-to-noise ratio with respect to the ambient sound (in cases where important ambient sound sources are behind the board),
- an improvement of the signal-to-noise ratio with respect to the background noise generated by the turbulent wind around the microphone.

The recommended microphone positions are shown in Figure 1.

5.3 Wind speed measurement at the turbine site

The wind speed should be determined according to one of the following methods with a preference for a determination at hub height according to clauses 5.3.1 and 5.3.2.

In the case of a wind farm, the wind speed should be measured at a point which is relevant for the noise generation. The following two examples, illustrated in Figure 5, can be used as guidelines.



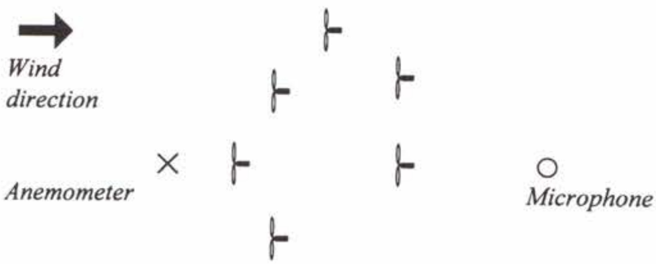


Figure 5. The upper part of the figure illustrates a case where the wind speed should preferably be measured at the closest turbine, while the lower part illustrates the case where the wind speed should be measured at an undisturbed position in the vicinity of the turbines.

In the first case, a major part of the noise is assumed to be generated by a turbine working in undisturbed flow and comparatively close to the microphone. The wind speed should then be obtained from the electric output of that turbine or from an anemometer placed at an undisturbed position in its vicinity.

In the second case, several turbines are assumed to give significant contributions to the immission sound level. Furthermore, it is not certain that the turbine closest to the microphone operates in undisturbed flow. The wind speed should then be obtained from the electric output of an undisturbed turbine or from an anemometer placed at an undisturbed position in the vicinity of the turbines.

5.3.1 Determination of wind speed from the electric power output and the power curve

Using this method, the wind speed is obtained from measurements of the electric power produced and a traceable power versus wind speed curve for the same type of wind turbine with the same components and adjustments.

If the power curve has been measured in compliance with the procedure described in Reference [8], the power curve gives the relation between the wind speed at hub height and the net electric power that the turbine delivers to the grid, provided that the air density is 1.225 kg/m^3. During the noise measurements the air density will not exactly have this value. Consequently, the power measured during the noise measurements must be converted to a standardised power in the following way:

$$P_s = P_m \frac{t_K}{t_{ref}} \cdot \frac{p_{ref}}{p} \qquad (2)$$

where P_s is standardised power (kW),
P_m is measured power (kW),
t_K is air temperature in K, $t_K = t_C + 273$, where
t_C is air temperature in ^oC,
t_{ref} is 288 K,
p is air pressure in kPa,
p_{ref} is 101.3 kPa.

The wind speed at hub height is obtained by reading the power curve at the power P_s.

For pitch controlled turbines, see Reference [8].

5.3.2 Determination of wind speed with an anemometer at hub height

Using this method, the wind speed is measured with an anemometer at a height over the local ground which equals the hub height ±25%. The anemometer height must not, however, be positioned below a height of 10 m. In the case of a single wind turbine, the anemometer should be located upwind of the turbine within $\pm 60^o$ and at a distance of between two and four rotor diameters from the rotor centre, see Figure 6. During the course of the test, the anemometer must never be in the wake of any portion of any wind turbine rotor or structure, see Reference [8].

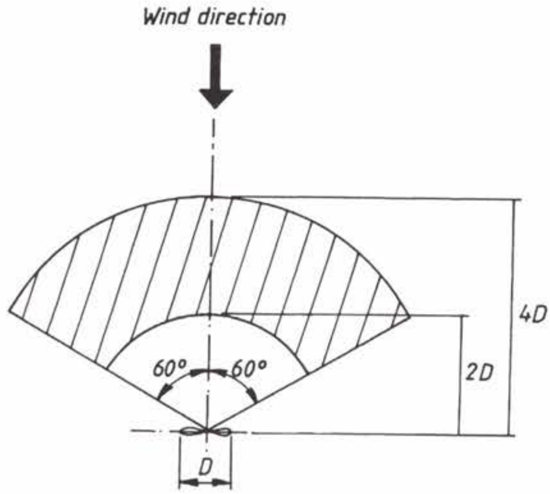


Figure 6. Recommended position of the turbine site anemometer for the case that the anemometer is positioned at hub height. D is diameter of wind turbine rotor.

5.3.3 Determination of wind speed with an anemometer at 10 m height

If it is impractical to make measurements at hub height, the wind speed may instead be measured at a height of 10 m above the local ground. In the case of a single wind turbine, the anemometer should be located upwind of the turbine and at a horizontal distance of between one and a half and four rotor diameters from the rotor. The anemometer must not be further than half a rotor diameter from a line through the rotor axis, in the wind direction and parallel with the ground surface, see Figure 7. During the course of the test, the anemometer must never be in the wake of any portion of any wind turbine rotor or structure, see Reference [8].

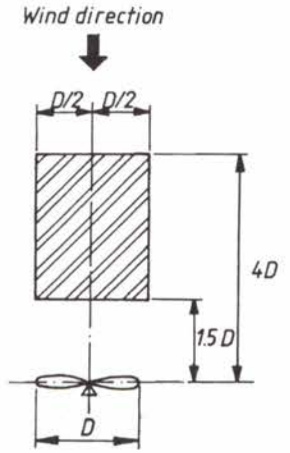


Figure 7. Recommended position of the turbine site anemometer for the case that the anemometer is positioned at 10 m height. D is diameter of wind turbine rotor.

5.4 Wind speed measurement position at the receptor

When the wind speed is measured at the receptor, a representative and open position in the vicinity of the microphone and at a height of 10 m above the local ground should be chosen. The position should be representative with respect to the ambient wind-induced sound at the receptor.

5.5 Wind direction measurement position

The wind direction should be determined at approximately the same position that the wind speed is measured. When the wind speed is measured at both the turbine and receptor sites, it is sufficient to determine the wind direction at the turbine site only.

5.6 Measurement technique

Measurements carried out according to the three methods described in this section should be fully supervised.

5.6.1 Method A

With the turbine(s) operating, $L_{Aeq,T}$ and wind speed are measured simultaneously at the receptor site and averaged over the same time intervals. The averaging time should be 1-10 minutes for each data pair. At least 10 data pairs should be obtained. The total measurement time should be at least 30 minutes.

The $L_{Aeq,T}$ of the background noise with the wind turbine(s) parked should be measured immediately before and/or after the combined noise measurements. The measurements of the background $L_{Aeq,T}$ should be carried out simultaneously with measurements of the wind speed at the receptor site. At least 10 data pairs should be obtained with the same averaging time as for the combined noise measurement. The total measurement time should be at least 30 minutes.

In cases where the target wind speed is defined with respect to the receptor location, at least three data points should be obtained above and at least three below the target wind speed with a maximum deviation of ±2 m/s from the target wind speed. The total measurement time for each of these groups should be at least 10 minutes.

The wind direction during the measurements should be obtained according to clause 5.5.

5.6.2 Method B

With the turbine(s) operating, $L_{Aeq,T}$ and wind speed at the turbine site are measured simultaneously and averaged over the same time intervals. The averaging time should be 1-10 minutes for each data pair. At least 10 data pairs should be obtained, of which at least three should be above and at least three below the target wind speed with a maximum deviation of ±2 m/s from the target wind speed. The total measurement time should be at least 30 minutes, and at least 10 minutes for each of the two groups of data pairs below and above the target wind speed.

The wind direction should be obtained according to clause 5.5.

5.6.3 Method C

With the turbine(s) operating, $L_{Aeq,T}$ at the receptor site should be measured simultaneously with the wind speeds at the turbine and the receptor sites, and be averaged over the same time intervals. The averaging time should be 1-10 minutes for each data triplet. At least 10 data triplets should be obtained, of which at least three should be above and at least three below the target wind speed with a maximum deviation of ±2 m/s from the target wind speed. The total measurement time should be at least 30 minutes, and at least 10 minutes for each of the two groups of data triplets below and above the target wind speed.

With the wind turbine(s) parked the $L_{Aeq,T}$ of the background noise should be measured immediately before and/or after the combined noise measurements. The background noise measurements should be carried out simultaneously with measurements of the wind speed at the receptor site. A total of at least 10 data pairs with an averaging time of 1 - 10 minutes should be obtained. At least three data pairs should be above and at least three below the wind speed corresponding to the target wind speed with a maximum deviation of ±2 m/s from that wind speed. The total measurement time should be at least 30 minutes, and at least 10 minutes for each of the two groups of data pairs.

If the measurements are carried out at a single turbine and the distance from the turbine site anemometer to the turbine tower along the wind direction, d, is large in the sense that

$$d \geq 0.1 v_{av} T_{av}, \qquad (3)$$

where v_{av} is a mean wind speed representative of the measurements,
T_{av} is the averaging time used,

a correction for the time, t, for the wind to pass the distance may be used as a delay to the sound averaging:

$$\Delta t = d / v_{av}, \qquad (4)$$

where d is the distance from the anemometer position to the wind turbine along the wind direction.

Alternatively, the averaging time T_{av} can be increased so that the condition given in Equation (3) is met.

No correction of this type should be used for a group of turbines.

The wind direction should be obtained according to clause 5.5.

5.7 Weather conditions

Measurements should not be performed when snow is present on the ground.

5.8 Measurement techniques for cases of low signal-to-noise ratios

As stated above, noise immission measurements around a wind turbine will often be influenced by background noise. If the equivalent continuous A-weighted sound pressure level of the turbine and the background is more than 3 dB over that of the background alone, the $L_{Aeq,T}$ of the turbine alone may be obtained by a correction for the background noise according to clause 8.2. However, if the level of the turbine and background exceeds that of the background with 3 dB or less, the level of the turbine alone cannot be obtained in that way. In such cases, the signal-to-noise ratio may be increased in one or several of the following ways.

5.8.1 Change of time of day for measurements

The background noise may be dependent on activities related to the time of day. Some typical examples are traffic noise, bird song, noise from playing children, etc. In such cases, the signal-to-noise ratio may be improved by carrying out the measurements during the night instead of the day.

5.8.2 Repositioning of microphone

In cases where the background noise is generated by sources close to or at the microphone, a repositioning of the microphone can be beneficial in order to obtain a more wind-sheltered position or an increased distance from ambient sound sources. This is permissible provided that the new measurement position fulfill all of the following requirements:

- the microphone is at the same height over local ground as at the original position,
- the type of terrain is the same at the new position as at the original position (small difference in ground impedance),
- the distance to the wind turbine is the same as the original distance within 5%,
- the angular position is the same as the original one with respect to the wind turbine within $\pm 5^{o}$ (for measurements in the downwind direction a deviation of $\pm 10^{o}$ is allowed). In the case of a group of wind turbines the angular positions should be referred to the turbine which gives the predominant contribution to the sound level at the original measurement point,
- the position is in similar location with respect to possible shielding of noise from the wind turbine(s) as for the original one.

It should be observed that if the microphone is repositioned, it may be necessary to reposition the receptor anemometer, as that anemometer should always be placed in the vicinity of the microphone.

5.8.3 Use of secondary windscreen

In cases where the signal-to-noise ratio is low due to wind noise in the microphone, a secondary windscreen can be beneficial. An example of such a windscreen is described in clause 4.2. It should be observed that a windscreen of this type may influence the frequency response. When this is the case, appropriate correction should be carried out.

5.8.4 Use of a large measurement board

As explained in clause 5.2.3, the large board can be used to reduce the influence of sound reflected from vertical surfaces behind the board, the wind-induced microphone noise (its effect can be compared with that of a secondary windscreen) and the influence of ambient noise generated by sources, shielded by the board.

If the board is used to reduce the wind induced microphone noise, the microphone should be positioned as close as possible to the point B in Figure 1 (the stagnation point on the board).

If the board is used to reduce the influence of ambient sources, shielded by the board, the microphone should be positioned at point A in Figure 1.

5.8.5 Approximate procedures

When problems with low signal-to-noise ratios appear, one or several of the techniques described in clauses 5.8.1 - 5.8.4 should be applied in the first place. If none of these are applicable or beneficial, one of the following techniques can be used. It should be observed, however, that the measuring accuracy will be lower in such cases.

5.8.5.1 Measurement at reduced wind speeds

The noise level from a wind turbine as well as background noise levels depend on wind speed. However, in many cases in practice, and especially in the case of horizontal axis turbines with fixed speed, the background noise level tends to decrease more rapidly with decreasing wind speed than the turbine noise. Thus, an improvement of the signal-to-noise ratio can be obtained by measuring at a reduced wind speed.

On the other hand, it is well known that the sound propagation from a wind turbine to a receiver is affected by the wind speed, especially in the upwind and downwind directions. It is, at present, difficult to quantify this effect. Thus, in order to retain a reasonable precision, it is recommended that the decrement in target wind speed should not exceed 2 m/s.

Such a change of wind speeds is permissible if the wind direction is the same and if the source strength of the turbine is known as a function of the wind speed. This technique can be used at a wind farm provided that all the turbines exhibit the same dependence of source strength on wind speed. The correction to be carried out in this case is given in clause 8.6.

This procedure should only be used together with method C.

5.8.5.2 Measurements at a reduced distance

A reduction of the measurement distance will, in general, increase the signal-to-noise ratio. For a single turbine site the distance may be reduced by 25%, provided that

- the distance to the new microphone position exceeds 1.5(H+D/2), where H is the hub height and D the rotor diameter of the wind turbine,
- the angular position is the same as the original one with respect to the wind turbine within $\pm 5^{o}$ (for measurements in the downwind direction a deviation of $\pm 10^{o}$ is allowed),
- the microphone is at the same height over local ground as at the original position,
- the type of terrain is the same at the new position as at the original one and the ground impe dance is similar to that at the receptor,
- the new location is similar to the original one with respect to possible shielding of noise from the wind turbine.

In the case of a group of turbines, a reduction of measurement distance of up to 25% (with respect to the turbine which gives the predominant contribution to the total sound level at the original measurement position) is also allowed, provided that

- the turbines do not exhibit strong directivity,
- all of the turbines have the same nominal sound power level at the time of measurement,
- the distance to the new microphone position from the closest wind turbine exceeds 1.5(H+D/2), where H is the hub height and D the rotor diameter of the turbine,
- the angular position is the same as the original one with respect to the closest wind turbine within $\pm 5^{o}$ (for measurements in the downwind direction a deviation of $\pm 10^{o}$ is allowed),
- the microphone is at the same height over local ground as at the original position,
- the type of terrain is the same at the new position as at the original one and the ground impedance is similar to that at the receptor,
- the new location is similar to the original measurement position with respect to possible shielding of noise from the wind turbines.

The sound levels obtained at a reduced distance must be corrected according to clause 8.7.

This procedure should preferably only be used together with method C.

6. MEASUREMENT OF A-WEIGHTED PERCENTILES

As an alternative to the measurement of $L_{Aeq,T}$ described in the previous chapter, one or several A-weighted percentiles can be determined.

6.1 Outline of the method

In this method, the noise from the wind turbine is measured at the receptor locations together with the wind speed, obtained from an anemometer positioned on a meteorological mast at the wind turbine or wind farm site. The background noise is also measured as a function of the wind speed obtained from the same anemometer.

Measurements specified in this chapter may be made with unattended recording equipment.

A-weighted percentiles may also be measured in conjunction with equivalent sound levels. When this is the case, the relevant parts of chapter 5 may be used.

The techniques described here are applicable for measurement of any A-weighted percentile L_{Ax}. However, it should be noted that the percentiles L_{A10}, L_{A90} and L_{A95} are the ones most often used in practice.

This method is used if the limits are expressed in percentiles and in particular where the noise immission limits are related to ambient sound measured previously at the receptor location.

6.2 Noise measurement positions

A free-standing microphone, a position on a building facade, or on a large vertical board can be used according to clause 5.2.

6.3 Positions for measuring wind speed and direction

The wind speed and direction should either be obtained from measurement equipment mounted at hub height on a meteorological mast at the wind turbine or wind farm site, or from an anemometer and a wind direction transducer at 10 m height according to the rules of clauses 5.3 and 5.5.

6.4 Measurement technique

The A-weighted percentiles L_{Ax} should be measured with the turbine operating during at least 20 periods of 10 minutes each when the wind speed equals the target wind speed ±2 m/s. For at least 10 of these periods the mean wind speed should be above the target wind speed and for at least 10 other periods the mean wind speed should be below the target wind speed.

If the combined noise levels are lower than the noise immission limits, then background noise measurements need not be carried out (compare method B in chapter 5). If, however, correction for ambient sound levels are required, the measurement procedure should be repeated with the wind farm parked.

When background noise measurements are carried out, they should be made over 20 periods of 10 minutes each when the wind speed equals the target wind speed ±2 m/s. During at least 10 of these periods, the mean wind speed should be above, and during at least 10 other periods the mean wind speed should be below the target wind speed.

6.5 Weather conditions

Measurements should not be performed when snow is present on the ground.

6.6 Techniques to be used in cases of low signal-to-noise ratios

The techniques described in clauses 5.8.1 - 5.8.4 may be used also for the A-weighted percentiles.

7. MEASUREMENT TECHNIQUE FOR NARROW BAND SPECTRA

Narrow band spectra are measured if it is a requirement to determine the tonality of the wind turbine noise at receptor locations. Tone levels can vary between measurements taken under nominally identical conditions. Two methods are recommended as follows. The simpler method uses the RMS narrow band spectrum and is described as 'Method I'. The second method uses individual short term spectra in addition to the RMS spectrum and is described as 'Method II'. It should be appreciated that the two methods only will give the same result for stationary tones. The choice of the method to be used in a specific case should be directed by relevant national guidelines.

A procedure for the evaluation of spectra is described in clause 8.8.

7.1 Measurement positions

The narrow band spectra can be regarded as a complement to the broad band noise levels determined according to chapter 5 or 6. Thus, the same microphone positions, anemometer locations, etc, should be used as during the determination of the broad band noise. However, it should be noted that measurement results obtained with vertical microphone boards may not properly describe the tone level and the masking of tonal noise by ambient sound. A secondary wind screen can be beneficial in order to avoid wind induced masking noise in the microphone.

It should be borne in mind that moving the microphone closer to the turbine(s) or measuring at lower wind speeds may also affect the amount of masking noise relative to the tone amplitude.

7.2 Method I

Measurements are undertaken using linear or C-weighting and must be undisturbed by extraneous noise sources. For fixed speed machines, 1 - 2 minute, RMS averaged narrow band spectra are obtained. If an FFT analyser is used, a Hanning window should be applied. It may be necessary to inspect similar spectra with higher frequency limits to ensure that tones present at higher frequencies are evaluated. In such cases, a similar approach is followed but using a higher frequency limit and a corresponding resolution.

The frequency resolution to be used depends on the tone frequency:

Tone frequency, Hz	Resolution, Hz
< 2000	2.0 - 5.0
≥ 2000	2.0 - 12.5

At least five RMS spectra are required within ±1 m/s of the target wind speed. Supplementary spectra should be obtained at wind speeds where the tones are deemed to be most significant.

For variable speed turbines at least 30 narrow band spectra (each averaged for 10 s) should be obtained within ±1 m/s of the target wind speed.

7.3 Method II

In addition to the measurements described in clause 7.2, short term, instantaneous spectra within the 1 - 2 minutes are obtained using the same parameters as described above. The time weighting should be as close as possible to time weighting characteristic 'F', that is, with an averaging time of 0.2 to 0.5 seconds. At least 50 spectra should be obtained for each 1 - 2 minute period; all the spectra obtained should be evaluated.

The analysis of non-stationary tones is quite intensive; it may therefore be convenient to record the signal to be analysed.

7.4 Measurement of background noise

The background noise is measured with the turbine(s) parked and immediately before or after the measurement of the turbine noise. In most cases in practice it is sufficient to measure according to Method I.

8. DERIVED RESULTS

8.1 Correction of values obtained with a measurement board

Measurement results obtained with a measurement board should be corrected in the following way

$$L_{free} = L_{board} - 6\,dB, \qquad (5)$$

where L_{free} is the corrected $L_{Aeq,T}$ or L_{Ax},
L_{board} is the measured $L_{Aeq,T}$ or L_{Ax}.

This correction applies to the combined noise level as well as the background noise level.

8.2 Correction of equivalent levels for background noise

After any necessary correction for the influence of the measurement board, the combined noise values obtained according to methods A and C are plotted against the average wind speed obtained from the anemometer at the receptor position. A linear wind speed scale should be used.

The values of the background noise with the turbine(s) parked are, after correction for the influence of the measurement board when appropriate, plotted in the same diagram and a second-order polynomial,

$$L_n = a + bv + cv^2, \qquad (6)$$

is fitted to these points by means of a polynomial regression, see Figure 8. In Equation (6),
L_n is the approximation of the background noise level,
v is the wind velocity,
a, b and c are the constants to be determined by the regression.

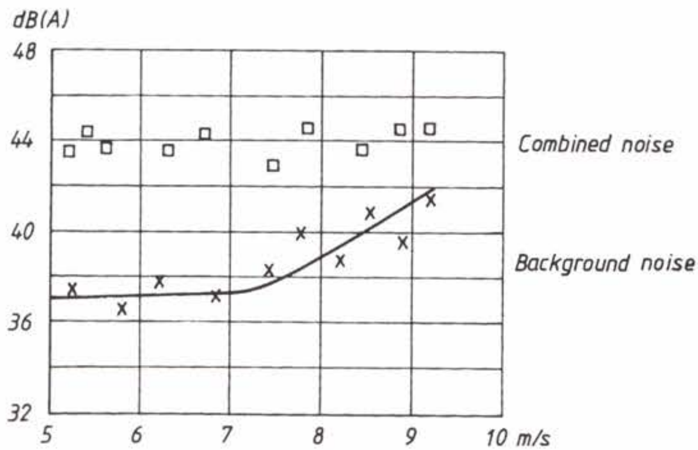


Figure 8. Example of plotting of combined and background noise levels versus wind speed at receptor site.

The measured combined noise levels of the turbine and the background, $L_{Aeq,free}$, are corrected with respect to the background noise levels at the same wind speed as read from the regression curve in the following way,

$$L_{Aeq,corr} = 10lg(10^{L_{Aeq,free}/10} - 10^{L_n/10}), \qquad (7)$$

where $L_{Aeq,corr}$ is the sound level of the wind turbine alone (the corrected value),
$L_{Aeq,free}$ is the combined level of the wind turbine sound and the background noise (the measured level),
L_n is the level of the background noise read from the regression curve at the same wind speed as the combined value.

When $L_{Aeq,free}$ - L_n is in the region of 3 - 6 dB, the corrected values should be marked with an asterisk. If $L_{Aeq,free}$ - L_n is 3 dB or less, this should be stated and $L_{Aeq,free}$ -3 dB be reported as an upper limit of the turbine noise.

8.3 Conversion of wind speed measured at the turbine site

The wind speed at the wind turbine site can be measured at different heights. In order to obtain comparable results, the measured wind speed should be converted to the corresponding wind speed at a height of either 10 m or the hub height. The conversion should be carried out using the logarithmic wind law and the roughness length of the site.

Thus, a wind speed measured at hub height can be converted to a height of 10 m in the following way

$$v_{10} = v_h \frac{\ln(10/z_0)}{\ln(h/z_0)}, \qquad (8)$$

where v_{10} is the converted wind speed,
v_h is the measured wind speed,
h is the height in m from ground to the anemometer,
ln is the logarithm to the base e,
z_0 is the roughness length of the site, expressed in m.

The roughness length of the site, z_0, can be estimated from the appearance of the upstream sector of the site, see Reference [10], and the following table:

Type of terrain	Roughness length, z_0, in m
Suburbs, provincial towns Shelter belts, forests Many trees and/or bushes	0.3
Farmland with closed appearance Farmland with open appearance Farmland with very few buildings, trees etc, airport areas with buildings and trees	0.05
Airport runway areas Mown grass Bare soil	0.01
Snow surfaces (smooth) Sand surfaces (smooth) Water areas (lakes, fjords, open sea)	0.001

If, on the other hand, the wind speed is measured at a height of 10 m and the wind speed at the hub height H is wanted, the conversion can be carried out using the following expression:

$$V_h = V_{10} \frac{\ln(H/z_0)}{\ln(10/z_0)}, \qquad (9)$$

8.4 Determination of the corrected equivalent level at the target wind speed

The background noise corrected values of the equivalent continuous A-weighted sound pressure level from the wind turbine are plotted against the average wind speed measured at the turbine site. When applicable, the wind speed should first be converted according to clause 8.3. A linear wind speed scale should be used. A straight line is fitted to the points by means of a linear regression, see Figure 9, and the value of $L_{Aeq,corr}$ at the target wind speed is determined from the line.

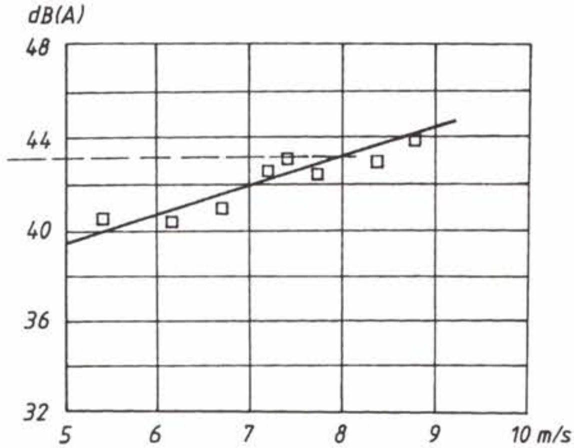


Figure 9. Example of determination of $L_{Aeq,corr}$ at 8 m/s. The wind speed is here the wind speed measured at the wind turbine site.

8.5 Determination of A-weighted percentiles at the target wind speed

After any necessary correction for the influence of the measurement board, the combined wind turbine and background noise levels are plotted against the average wind speed measured at the turbine site. When applicable, the wind speed should first be converted to the desired height according to clause 8.3. A linear wind speed scale should be used. A straight line is fitted to the points by means of a linear regression, in a similar manner to that shown in Figure 9 for $L_{Aeq,T}$ levels. The combined value of the turbine noise and background noise at the target wind speed, $L_{Ax,comb}$, can then be determined from the line.

If it is necessary to correct for background noise then the above procedure should be repeated for the measurements obtained with the wind turbine(s) parked. From a linear regression on these data the level of the background noise at the target wind speed, $L_{Ax,back}$, can be determined.

The combined noise level is corrected for background noise to give the corrected percentile sound level of the wind turbine(s) alone at the target wind speed, $L_{Ax,corr}$, using Equation (10),

$$L_{Ax,corr} = 10lg(10^{L_{Ax,comb}/10} - 10^{L_{Ax,back}/10}) \quad (10)$$

It is recognised that the correction method above only strictly applies to the correction of one $L_{Aeq,T}$ by another. Readers are referred to the paper by Nelson, Reference [9], for more discussion on correcting percentile measurement results.

8.6 Correction of values obtained at reduced wind speeds

The noise levels obtained at reduced wind speeds should be corrected for background noise as described in clause 8.2. The wind speeds should, when applicable, be converted according to clause 8.3. A reduced target wind speed is chosen as the mean value of the converted wind speed during the measurements. The level at the reduced target wind speed should be corrected in the following way

$$L'_{Aeq,corr} = L_{Aeq,low} + \Delta L_A \quad dB, \tag{11}$$

where $L'_{Aeq,corr}$ is the immission noise level to be reported,
$L_{Aeq,low}$ is the background corrected noise level at the reduced target wind speed.

The term ΔL_A should be obtained from data obtained in the procedure described in clause 6.3 in Reference [1]. It is defined as

$$\Delta L_A = L_{target\ ws} - L_{meas\ ws}, \tag{12}$$

where $L_{target\ ws}$ is the background corrected noise level at the reference point at the target wind speed under reference conditions, $L_{Aeq,ref}$ according to clause 6.3 in Reference [1],
$L_{meas\ ws}$ is $L_{Aeq,ref}$ according to Reference [1] at the reduced target wind speed.

The value of ΔL_A obtained for another turbine of the same type can also be used provided that the adjustments and components of the two turbines are the same.

8.7 Correction of values obtained at a reduced distance

In the case of a single turbine, the measurement results obtained at a reduced distance should be corrected in the following way

$$L''_{Aeq,corr} = L_{Aeq,red} - 20\lg\left(\frac{R_1}{R_2}\right) \quad dB, \tag{13}$$

where $L''_{Aeq,corr}$ is the immission noise level to be reported,
$L_{Aeq,red}$ is the measured noise level at the modified microphone position, corrected for measurement board and background noise,
R_1 is the distance from the hub of the turbine to the original microphone position,
R_2 is the distance from the hub of the turbine to the modified microphone position.

For a group of wind turbines with the same source strength, the corrected level is obtained as

$$L''_{Aeq,corr} = L_{Aeq,red} - 10\lg\left(\frac{\sum_i \frac{1}{R_{2i}^2}}{\sum_i \frac{1}{R_{1i}^2}}\right) \quad dB, \tag{14}$$

where $L''_{Aeq,corr}$ is the immission noise level to be reported,
$L_{Aeq,red}$ is the measured noise level at the modified microphone position, corrected for measurement board and background noise,
R_{1i} is the distance from the hub of turbine i to the original microphone position,
R_{2i} is the distance from the hub of the turbine i to the modified microphone position.

8.8 Determination of tone levels

The tonality is described as the difference between the sound pressure level of the tone and the broadband noise over a range of frequencies around the tone which masks the audibility of the tone. The frequency range of the 'masking noise' is known as the critical band and is defined in the table below:

Centre frequency f_c, Hz	20 - 500	Above 500
Critical bandwidth	100 Hz	20% of f_c

National standards or guidelines with other definitions may take precedence.

If a single tone is present, the critical band is centred upon the tone (the lowest band being 20 - 120 Hz). For tones between 20 and 70 Hz, the critical band should be chosen as 20 - 120 Hz. If more than one tone is present, the critical band is placed so that it contains the maximum possible amount of tonality as defined in clause 8.8.4.

The analysis of tonality comprises four steps:

A. Identification of the lines in the spectra as either tones, masking or neither.
B. Calculation of masking level.
C. Calculation of tonal noise level.
D. Calculation of tonality.

8.8.1 Identification of lines in spectra

In order to position the critical band and to calculate tone and masking noise levels, each line in the 1 - 2 minute spectrum must be classified according to the following criteria. If it is apparent that a 1 - 2 minute integration time is too long for variable speed machines, a shorter integration time should be used, e.g. 10 s, without reducing the total analysis period.

- A peak is identified as a tone if its level is more than 6 dB above $L_{pn,avg}$.
- If the peak qualifies as a tone, the adjacent lines are also classified as tonal noise if their levels are within 10 dB of the peak and more than 6 dB above $L_{pn,avg}$.
- If a spectral line is more than 6 dB above $L_{pn,avg}$ and more than 10 dB below the peak level it is classified as neither tone nor masking.
- All lines below $L_{pn,avg}$ +6 dB are classed as masking.

$L_{pn,avg}$ may be determined in the following way:
- The 70% of the lines within the critical band which have the lowest levels are identified. The energy averaged sound pressure level of these lines is determined and denoted $L^{70\%}$.
- $L_{pn,avg}$ is determined as the energy average of all lines below ($L^{70\%}$ + 6 dB).

Alternatively, the tones and masking noise may be identified iteratively according to the criteria above, see Reference [11].

When the level of the masking noise has a steep gradient over the critical band, it may be preferable to determine the masking noise as a function of frequency, $L_{pn}(f)$, from a linear regression through all spectral lines defined as masking, see Reference [12]. All lines with a level of at least 6 dB above $L_{pn}(f)$ are classed as tones. Adjacent lines are also classified as tonal noise if their level is within 10 dB of the peak and greater than 6 dB above $L_{pn}(f)$ at the same frequency. If a spectral line is more than 6 dB above $L_{pn}(f)$ and more than 10 dB below the peak level it is classified as neither tone nor masking.

The process described above is repeated for every critical band centred around tonal peaks in the spectrum. The result is that within each critical band every spectral line is classified as belonging to tonal noise, masking noise or neither.

8.8.2 Calculation of masking noise level

The masking level in the critical band, L_{pm}, is calculated using the lines classed as masking and correcting for a reduction in the number of lines due to the exclusion of tones and for the influence of the Hanning window,

$$L_{pm} = 10lg(\sum 10^{L_m/10}) + 10lg\frac{critical\ bandwidth}{N_m \times \Delta f} + 10lg\frac{1}{1.5}, \qquad (15)$$

where L_m is the sound pressure level of each line classified as masking noise,
N_m is the number of lines within the critical band classified as masking noise,
f is the nominal frequency resolution.

8.8.3 Calculation of tonal noise level

Method I

For each tone, the tone energy within the critical band, L_{pt}, is calculated using the lines identified as tonal noise from the spectrum. A correction is made for the use of a Hanning window if the tones occupy two or more lines,

$$L_{pt} = 10lg(\sum 10^{L_t/10}) + 10lg\frac{1}{1.5}, \qquad (16)$$

where L_t is the sound pressure level of each line classified as tonal noise.

In the case where several tones exist within the same critical band, the total level of the tones, L_{ptI} is calculated as

$$L_{ptI} = 10lg(\sum_i 10^{L_{pti}/10}), \qquad (17)$$

National standards or guidelines with other definitions may take precedence.

Method II

For the short term spectra of 0.2 to 0.5 s, the total sound pressure level, L'_{pti}, is calculated for each tone i using the lines classified as tonal noise. A correction is made for the Hanning window effect if the tone occupies two or more lines,

$$L'_{ptI} = 10lg(\sum_i 10^{L_{pti}/10}) + 10lg\frac{1}{1.5}, \qquad (18)$$

where L_t is the sound pressure level of each line classified as tonal noise,

In the case where several tones exist within the same critical band, the total level of the tones, L'_{pt}, is calculated as

$$L'_{pt} = 10lg(\sum_i 10^{L'_{pti}/10}), \qquad (19)$$

The tone level used in the assessment, L_{ptII}, is the arithmetic mean of the highest 10% of tone levels, L'_{pt}, from the short term spectra.

8.8.4 Calculation of tonality

The audibility of a tone is dependent upon the tonality and the mid-frequency of the critical band. For each of the 1 - 2 minute periods, the tonality, L_{tmI}, or L_{tmII}, is calculated as

$$\Delta L_{tmI} = L_{ptI} - L_{pm}, \qquad (20)$$

$$\Delta L_{tmII} = L_{ptII} - L_{pm}, \qquad (21)$$

For each period, the tonality of the most significant tone(s) should be reported.

9. UNCERTAINTY

The uncertainty of the measured noise level should be expressed as a standard deviation s. The resulting standard deviation is determined by adding contributions from independent sources of variance:

$$s = \sqrt{\sum s_i^2}. \tag{22}$$

For sources of variance for which a uniform distribution within a range ±a is assumed, the standard deviation may be estimated as s = a/3. For example this applies to the uncertainty due to calibration.

A major source of uncertainty is the influence from the background noise, especially when the level is close to the total noise level. Generally, the standard deviation s_c of the corrected turbine noise level, L_{corr}, is

$$s_c = \frac{\sqrt{s_{tot}^2 \cdot 10^{2L_{tot}/10} + s_{back}^2 \cdot 10^{2L_{back}/10}}}{10^{L_{corr}/10}}, \tag{23}$$

where s_{tot} and L_{tot} are the standard deviation and the level of the combined noise from turbine and background,
s_{back} and L_{back} are the standard deviation and the level of the background noise,
L_{corr} is the level of the turbine noise corrected for the influence of the background noise.

When regression analysis (on N measurements) is used to determine the level of the background noise, the standard deviation may be found from the residual variance;

$$s_{back} = \sqrt{\frac{\sum (L_{back,meas} - L_{back,est})^2}{N-2}}, \tag{24}$$

where the summation extends over the N measurements.

10. INFORMATION TO BE RECORDED AND REPORTED

10.1 The wind turbine and receptor sites

The positions of the wind turbine and receptor sites and their environments should be fully described. The following list defines the parameters to be recorded and reported.

Information to be recorded and reported

- Position of wind turbine(s) and receptor. Photographs, topographical maps and, where available, coordinates in a national coordinate system should be included,
- type of topography (hills, flat terrain, cliffs, mountains, etc., for nearest 2-3 km),
- type of ground (grass, sand, etc.),
- nearby reflecting structures such as building structures,
- sound sources such as trees, bushes, water surfaces, irrelevant wind turbines, highways, industrial complexes, airports, coastline, which may affect the background level.

10.2 Characterisation of the wind turbine(s)

The wind turbine or the group of wind turbines and their operating conditions should be as completely specified as possible.

Information to be recorded and reported

- Manufacturer, type and serial number of wind turbine(s), if available,
- rated power,
- hub height,
- tower type.

10.3 Instrumentation

Information to be recorded and reported

- The equipment used for the measurements, including type, serial number, name of manufacturer and latest date of calibration,
- bandwidth (or number of spectrum lines) of narrow band frequency analyser,
- position and size of microphone board (when appropriate),
- microphone position,
- elevation of the microphone positions with respect to the wind turbine base.

10.4 Acoustic data

All measured data should be recorded. In addition, the following derived data should be recorded and reported:

Information to be recorded and reported

Data obtained according to Method A:

- The corrected sound level, $L_{Aeq,corr}$, or, when appropriate, the corresponding level obtain using the approximate procedure with reduced distance, $L''_{Aeq,corr}$,
- the background noise, corrected for microphone board.

Data obtained according to Method B:

- The free-field sound level of the combined noise, $L_{Aeq,free}$.

Data obtained according to Method C:

- At target wind speed, the corrected sound level $L_{Aeq,corr}$ or, when appropriate, $L'_{Aeq,corr}$ or $L''_{Aeq,corr}$,
- $L_{Aeq,corr}$ (or $L'_{Aeq,corr}$ or $L''_{Aeq,corr}$) as a function of wind speed at 10 m height or hub height,
- the background noise, corrected for microphone board, as a function of the wind speed at the receptor.

Data obtained according to chapter 6:
At the target wind speed

- The combined value of the turbine noise and background noise, $L_{Ax,comb}$,
- the level of the background, $L_{Ax,back}$,
- the corrected sound level of the wind turbine(s) alone, $L_{Ax,corr}$.

Additional data for all methods:

- Information on the use of approximate procedures, if any, according to clause 5.8.5,
- estimated uncertainty of the corrected free-field sound level,
- the tonality L_{tmI} or L_{tmII}, if required.

10.5 Non-acoustic data

Information to be recorded and reported

- Time and date when the measurements were performed,
- temperature and barometric pressure,
- turbulence or cloud cover and altitude of the sun,
- locations of anemometers and wind direction transducer.

11. ACKNOWLEDGEMENTS

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12. REFERENCES

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[2] IEC Publication 651. Sound level meters.

[3] IEC Publication 804. Integrating-averaging sound level meters.

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APPENDIX 1.
CHOICE OF FREE-FIELD MEASUREMENT POSITIONS

It is a common experience when performing outdoor measurements that sound propagates from source to receptor along several paths. Figure 10 shows a typical example where sound from a wind turbine is transmitted to a microphone along a straight path TM (direct sound including ground reflection) and along a path TFM which involves a reflection from the facade of a building (reflected sound). This implies that the sound level which is measured in such a situation depends not only on the source strength and the distance between source and receptor but also on a factor which is hard to assess, namely the characteristics of the reflecting surface.

For this reason, authorities in several countries specify that the limits for sound immission refer to a level measured at a point where either the reflection conditions are well defined (similar to those described in clauses 5.2.2 and 5.2.3 in this guide), or where the level of the reflected sound is low enough. In the latter case, the level is often referred to as a "free-field" value. The "free-field" value is here defined as the level at a point where the level of the reflected sound is 6 dB or more below that of the direct sound (including ground reflections in both cases).

In this appendix, some guidelines are given on how to position the microphone in order to obtain a free-field value. There is insufficient knowledge to treat all possible cases, and so the present discussion is limited to three typical cases. In these cases the sound is assumed to be generated by a single source. However, the recommendations given can easily be extended to a group of turbines.

In the simple case A, which is characterized by a microphone position within the shaded area in Figure 10, a pronounced reflection can be expected according to the laws of geometrical acoustics. The criterion that the level of the reflected sound should be at least 6 dB below that of the direct sound implies that

$$TFM \geq 2 \cdot TM. \qquad (25)$$

This rule can readily be adopted to cases where the sound is reflected in several vertical surfaces.

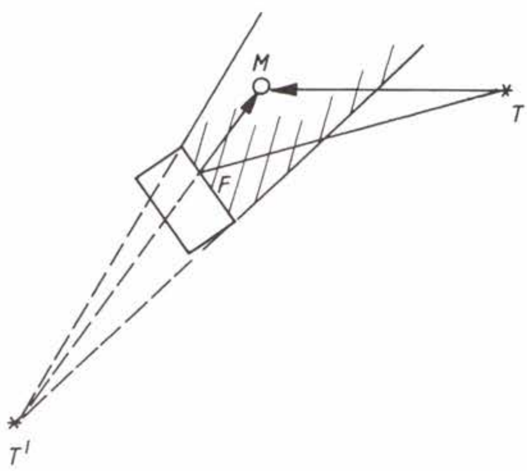

Figure 10. Illustration of the concepts of direct and reflected sound in case A. T indicates the position of the wind turbine and T´ the position of the mirror source.

It has been pointed out[1] that reflections in case A can be neglected if the distance between the reflecting surface and the microphone is large compared with the dimensions of the reflecting surface. As an example, it is stated that the reflection from a surface with the dimensions of 4 m x 8 m can be neglected if the distance is more than 50 m.

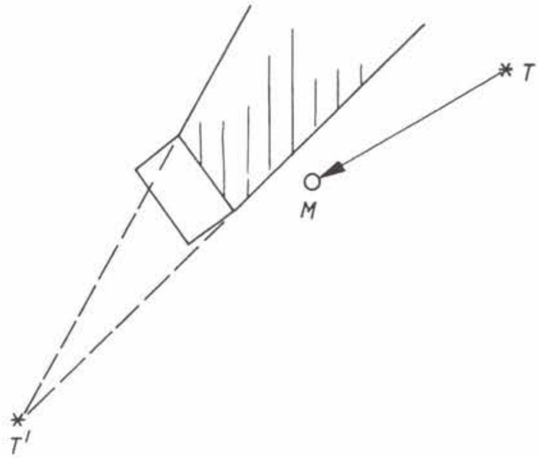

Figure 11. Illustration of case B.

In case B, which is illustrated in Figure 11, the microphone is positioned just outside the area where a pronounced reflection can be expected according to the laws of geometrical acoustics. This case is more difficult to treat than case A. If the surface is very smooth, the laws of geometrical acoustics could be applied. The level of the reflected sound will then be comparatively low. However, field experiences show that this is not always the case. Surface unevenness often give strong reflections in directions other than those expected when applying the theory of geometrical acoustics on the facade outline. If no other information is available, it is recommended that the same criterion is used for this case as for the previous one, that is, equation (25) is assumed to be valid also here (point F is chosen as the nearest part of the facade).

Case C is illustrated in Figure 12. The measuring point is situated 'beside' a building. Field experiences indicate that a free-field value will be obtained if the distance between the microphone and the building is at least 5 m.

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[1] Metod för immissionsmätning av externt industribuller (Method for the measurement of noise immission from industrial plants). Naturvårdsverket (The Swedish Environmental Protection Agency).

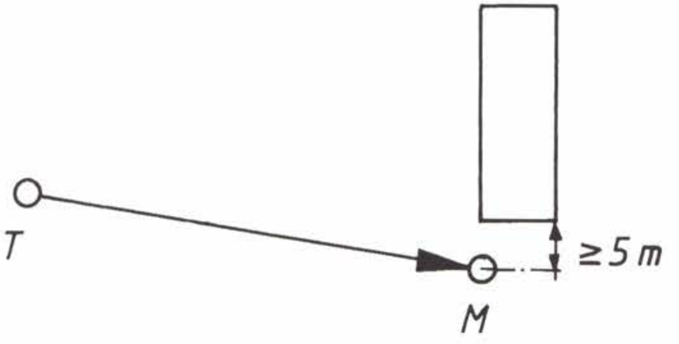

Figure 12. Illustration of case C.

It should be observed that in many cases in practice, the problems involved with choosing a microphone position for a free-field value can be avoided by using a measurement board as described in clauses 5.2.2 and 5.2.3.

APPENDIX 2.
MEASUREMENT AT PREFERRED PROPAGATION CONDITIONS FOR IMPROVED MEASUREMENT REPRODUCIBILITY

The immission limits given by authorities are often expressed as certain equivalent sound levels or A-weighted percentiles which must not be exceeded at specified points in the vicinity of the wind turbine generator or generators. The important questions on wind speed and wind direction are thus left unspecified. It is the purpose of this appendix to give some additional recommendations which can be used when no other information is available.

A. Wind speed

The wind speed should be 8 m/s measured at a height of 10 m according to clause 5.3. It may also be measured at a higher point but the value must then be corrected to 10 m height according to clause 8.3.

B. Wind direction

The choice of wind directions for measurements is determined by both propagation and directivity effects. Thus, the levels obtained at a receptor location depend on the wind direction during the measurements. This phenomenon also appears during measurements of several other types of outdoor sources; industrial plants, road traffic, etc. The variations of the sound levels make it time-consuming to obtain a true equivalent value which is representative for a long time, for instance a year. It has also been shown that the measurement reproducibility is fairly low when a true equivalent value is sought for a relevant distribution of wind directions, but high when all the measurements are carried out during favourable propagation conditions, that is, in the downwind direction and in the presence of a moderate temperature inversion (stable atmospheric stratification).

In order to cope with the measurement problem in these cases, several countries have established a policy to the effect that measurements of noise from roads, industries, etc, are performed during favourable weather conditions only. Thus, the values obtained in this way can be regarded as conservative estimates of the equivalent levels for a whole year.

This policy can also be used for the determination of an immission level from a wind turbine or a group of turbines, as described below.

In general, the measurements should be performed when the wind is blowing within $\pm 45^{o}$ of the direction from the turbine (or from the wind turbine dominating the receptor level) towards the measurement point.

However, the level from a single turbine can be systematically higher in directions other than the downstream one due to source directivity. Such a directivity effect is usually related to a presence of machinery noise in the form of tones; it should be recognized that also the presence of audible tones could be an adverse factor.

Therefore, the directivity of the wind turbine and the presence of tones should be checked. This can be done in two ways. The preferred method is to consult the results from an emission measurement, carried out according to Reference [1] or a similar procedure. If the directivity in the crosswind or upwind directions is 3 dB or more, or if pure tones are more important in the crosswind or upwind directions than in the downwind one, the measurements should additionally be carried out during the wind directions (within ±45°) corresponding to the strongest directivity and/or highest tone level.

If no such information is available, a listening test should be done. A restriction to downstream immission measurements is permissible if no tones are heard in the crosswind or upwind directions. In the opposite case, the results from an emission test must be consulted.

C. Temperature gradient

The temperature gradient in the lowest 10 m of the atmosphere, dT/dz (where T is the temperature and z the elevation), should be in the interval -0.05° C/m < dT/dz < 0.05° C/m. This gradient depends mainly on wind speed, position of the sun and cloud cover.

The present requirement can be expected to be satisfied if[2]:

- the measurement is performed at night time (one hour before sunset to one hour after sunrise), or
- the measurement is performed at day time (one hour after sunrise to one hour before sunset) with a cloud cover > 4/8.

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[2] C. Larsson: "Weather Effects on Sound Propagation Near the Ground". Second International Congress on Recent Developments in Air- and Structure-borne Sound and Vibration, Auburn 1992. Proceedings, p 1269-1276.

APPENDIX 3.
ASSESSMENT OF THE AMBIENT SOUND AT A SITE

A. Introduction

In some countries noise limits are set relative to existing ambient sound levels, and special procedures are recommended for the measurement and assessment of the ambient sound. In the absence of such recommendations, the following information can be used.

B. Identification of properties where ambient noise surveys are required

Before the wind farm is constructed, the developer/operator should identify the nearest noise sensitive properties to the wind turbines.

If there are a number of such properties, an ambient noise survey will be required at each one.

If there are rather more properties, it may be appropriate to identify a smaller number of properties, in agreement with the local authority, that have ambient noise levels each representative of a group of properties in their immediate vicinity. An ambient sound survey will be required at each one of these indicative properties as the noise limits relate to the existing ambient sound levels.

The precise locations at which the ambient sound surveys should be made at each property should be agreed in consultation with the local authority.

C. The ambient sound survey

The ambient sound survey should be taken over a sufficient period of time to enable a reliable assessment of the prevailing ambient sound levels at each property to be made. As a guideline, an appropriate survey period might be one week, although the actual duration will depend upon weather conditions, in particular the wind speed and direction during the survey period. It must be ensured that, during the survey period, wind speeds over the range zero to at least 12 m/s (10 minutes average at 10 m height), and a range of wind directions as are typical of the site, are experienced.

The aim of the survey, at each location, is to characterise the variation in prevailing ambient sound level with wind speed. This is achieved by correlating ambient sound measurements with wind speed measurements made over identical time periods. The following sections identify the measurements required to enable this.

C.1 Acoustic measurements

Ambient sound levels should be measured using the A-weighted L_{Ax} percentiles over consecutive 10 minutes intervals, L_{A90} and L_{A95} are those more often employed.

The equipment should fulfill the requirements given in chapter 4. The microphone should be mounted on a tripod at 1.2 - 1.5 m above ground level, fitted with a windscreen, and placed in the vicinity of, and external to, the property, and in a free-field position according to clause 5.2.1.

C.2 Wind speed and direction measurements

Wind speed and direction data should be recorded as average values over 10 minutes intervals, these intervals to be synchronised with the measurement period for the sound.

The measurements should preferably be made using instruments mounted at 10 m height. Where this is not possible, wind speeds measured at one height can be converted to the value that would have been measured at 10 m height using the expression (8) in clause 8.3.

The instruments should be mounted on a mast positioned on the site so that they give a reasonable description of meteorological conditions at the noise sensitive properties. Where there are several masts on a site, data from the instruments mounted on the mast closest to each property should be used.

C.3 Data reduction

At the end of the survey period, data recorded during periods of rainfall, or immediately afterwards, where rainfall may have affected flow in nearby rivers or streams, should be discarded.

Two sub-sets of data should be created, for the following periods:
- quiet waking hours (e.g., 18.00 - 23.00 every day, 13.00 - 18.00 on Saturday, 07.00 - 18.00 on Sunday),
- night hours (e.g., 23.00 - 07.00, every day).

These two sub-sets are identified as the 'day time' data and the 'night time' data.

For each sub-set, a 'best-fit' curve should be fitted to the data using a least squares approach, usually a polynomial model (of no more than 4th order).

Where there is considerable scatter in the data, it may be appropriate to bin the acoustic data into 1 m/s bins, before identifying a best fit model.

These two curves, referred to as the 'day time curve' and the 'night time curve', provide a characterisation of the prevailing ambient noise levels, for the day- and night-time respectively, as functions of wind speed from zero to 12 m/s at 10 m height.

Note that whatever model is used to describe the measured data, this should not be extrapolated outside of the range of measured wind speed data.

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