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# INDUSTRIAL NOISE SOURCES – METHODS OF MEASUREMENT AND ESTIMATION

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## 1. INTRODUCTION

The initial parameter for determining the sound pressure level around the industrial plant is the sound power level, where the industrial plant may be treated as a whole as one noise source, with one value of sound power level subordinated to it, or the plant may be treated as a set of noise sources with given values of the sound power level.

In the case of the industrial plant treated as a single noise source, as hitherto experience has shown, the determination of the sound power level is burdened with a large error. This is why it is better to treat it as a set of noise sources.

In Poland an instruction has been developed [2] with the goal of unifying the noise sources found in the industrial plant area.

First of all, the sources are divided into stationary and mobile.

Among the stationary sources we differentiate, depending on the geometrical dimensions, between the following sound sources: point, linear, surface, including "building" type, and spatial.

Since in the calculating model all the sound sources are brought down to a set of point sources with a given sound power level $L_W$, then depending on the type of source there may be a need to substitute it by partial sources.

The accepted principles of describing the various types of sources by a point source are given below.

## 2. STATIONARY SOUND SOURCES

### 2.1. Point sound source

The sound source may be treated as a point source when each of its linear dimensions (height, length, width) is smaller than the half distance between the source and the closest observation point, i.e.:

$$r \geq 2l \tag{1}$$

where: l - the greatest linear dimension of the sound, m r - the distance from the geometrical center of the source to the observation point, m

**2.2. Linear sound source with a finite length**

The linear sound source is a source, whose two linear dimensions with respect to a third one may be omitted and at the same time this dimension is greater than the half distance from the geometrical center of the source. Hence the source should be divided into equal segments of such a length to fulfill condition (1), and it is assumed that at the entire length the source emits a sound on the same level.

The "division" of the source into point sources is carried out according to the relationship:

$$L_{Wn} = L_W - 10\lg n, \quad dB \tag{2}$$

where: $L_W$ - the sound power level of the entire linear source, dB

n - the number of segments, into which the source should be divided in order to fulfill condition (1).

**2.3. Surface sound source**

The surface sound source, whose one linear dimension in relation to the two remaining ones may be omitted and these two dimensions are greater than the half distance from the geometrical center of the source.

**2.3.1. The source situated in an open space.** The source, which is situated in an open space may have a horizontal or vertical orientation. In both cases the surface source should be divided into point partial sources according to the relationship:

$$L_{Wn} = L_{Wb} - 10\lg n, \quad dB \tag{3}$$

where: $L_{Wp}$ - the sound power level of the entire surface source, dB

n - the number of fields, into which the source should be divided into in order to fulfill condition (1)

**2.3.2. Building-type source.** The building-type source is a certain variation of the surface source appearing in the industrial plant. In this case the sound sources are found inside, e.g. in the industrial hall and the wall and ceiling surfaces become secondary noise sources.

For this type of source the partial sound power level of the substitute point source is calculated from the relationship:

$$L_{Wn} = L_{in} + 10\lg S - R - 6, \quad dB \tag{4}$$

where: $L_{in}$ - the sound pressure level inside the hall at a distance of about 1 m from each wall and ceiling, dB

S - the partition surface, for which the condition (1) is fulfilled, i.e. the entire partition or its part, $m^2$

R - airborne sound insulation of the entire partition or its part presented, dB

When the wall or its part consists of elements of differing airborne sound insulation (e.g.: brick + glass) formula (4) should also include resultant insulation, calculated according to the formula:

$$R = 10\lg \frac{S}{\sum S_i \cdot 10^{-0,1R_i}}, \quad dB \tag{5}$$

where: S - $\Sigma S_i$, $m^2$
$S_i$ - surface of the I-element with insulation $R_i$, $m^2$
$R_i$ - airborne sound insulation of the I-element, dB

**2.4. Spatial sound source**

The spatial source is a source situated outside of the buildings and each of its linear dimensions is greater than the half distance from the geometrical center of the source. An example of this type of source is a ventilator cold store or a set of ventilators with cyclones.

In order to create a model of such a source it must be "shut off" in a solid in the shape of a cubicoid with demisions approximating as much as possible the demisions of the source. Each side of the source becomes a surface source with a given sound power level. In this case it would most correct to determine, on the basis of measurements of, for example, the sound intensity, the sound power level of each surface.

A certain simplification, assuming that this source emits energy uniformly in all directions, may be the determination of the power level of the various surfaces according to:

$$L_{Wb} = L_W - 10\lg n, \quad dB \qquad (6)$$

where: $L_W$ - the sound power level of the entire spatial source, dB
n - the number of surfaces considered in the division (4 or 5 or 6)

Knowing the sound power level of the partial surface sources it is necessary to state whether condition (1) is fulfilled, i.e. whether these sources may be treated as point sources in further deliberations. If condition (1) is not fulfilled, a further division of the source should be carried out according to the principle given in pt. 2.3.1.

## 3. MOBILE SOUND SOURCES

In the majority of industrial plants it is the stationary sound sources that decide on the acoustic parameters. The acoustic evaluation should also consider the sound sources moving within the plants in an organized way, for example the overhead crane and a random way, i.e. truck transport.

For the needs of this method we have adopted simplifications, compared to methods for evaluating transport noise, allowing us to estimate the range of the noise emitted by means of transport found on the grounds of the given plant. The route along which each mobile source moves on, or the area on which they move, are changed into a set of substitute point sound sources and/or each parking space is identified, substituting it with a equivalent sound power level according to:

$$L_{W_{eqn}} = 10\lg\left[\frac{1}{T}\sum_{n=1}^{N} t_i 10^{0,1 L_{Wn}}\right], \quad dB \qquad (7)$$

where: $L_{weqn}$ - the equivalent sound power level for n - of this sources, dB
$L_n$ - the sound power level for the given mobile option, dB
$t_i$ - duration of the given mobile operation, s
N - the number of mobile options in time T
T - the period of evaluation, for which the equivalent level is calculated, s

## 4. THE MEASUREMENT METHODS USED

The basic measurement method used to determine the sound power level of a noise source in open field conditions is the measurement of the sound pressure level on the cap sealing off the given noise source [7]. This method is limited by the fact that the device being the subject of measurement is relatively small. In the case of large linear and surface sources (with the exception of the building) the sound power level is attained with satisfactory precision using the methods described in VDI [10, 11]. The greatest measurement problem is the spatial source. In this case the intensity method is applied [9].

## 5. DETERMINING THE EXPECTED SOUND PRESSURE LEVEL IN THE ENVIRONMENT

The value of the sound pressure level in the observation point from the "n" single industrial noise source is determined according to the principles in force taking into consideration the actual level of the sound power of this source and the conditions of the propagation of the sound wave described by corrections D. The general noting of this relationship is as follows:

$$L_n = L_{Wn} + \Delta, \text{ dB} \qquad (8)$$

where: $L_{Wn}$ - the actual sound power level of the point source considering the place of positioning and the indicator of direction - emission,

$\Delta$ - the sum of corrections influencing the conditions of sound wave propagation from the real source and from the mirror source.

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# A NEW APPROACH TO WIND TURBINE NOISE MEASUREMENT

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## INTRODUCTION

Currently available wind turbine noise measurements are not sufficiently detailed to enable the sources of such noise to be fully characterised. This is because published noise data, prepared to IEA or equivalent standards, is based on averages over one or two minutes. Since wind turbine noise is a function of the wind speed, it is necessary to take measurements at *fixed* wind speeds in order to determine the noise source characteristics. Figure 1 (below) shows the average atmospheric turbulence spectrum. A peak variation exists at a timescale of approximately one minute; therefore it is inevitable that any measurements averaged over two minutes will include more than one wind condition. Wind direction also changes constantly, which makes it difficult to maintain microphones in fixed orientations relative to the wind turbine's axis.

It has been observed that short periods of stable wind up to 30s in length occur naturally. An experiment has been performed to capture these naturally occurring periods of steady wind conditions, in order properly to characterise wind turbine noise sources with respect to the controlling parameters, particularly the wind speed.

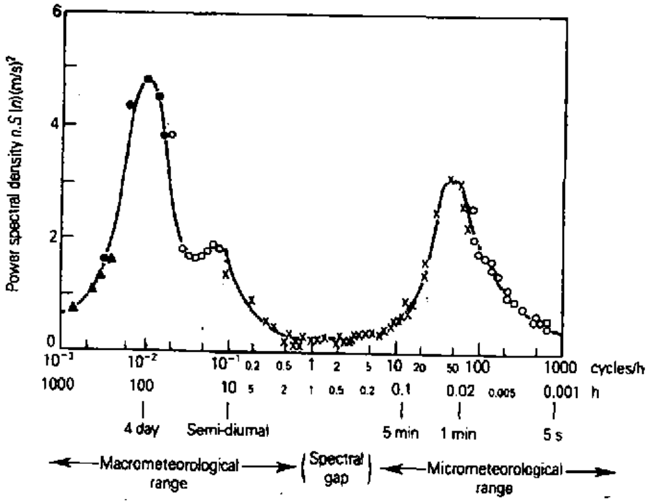


**Figure 2.1** Spectrum of horizontal wind speed at Brookhaven National Laboratory [2]

**Figure 1: average wind turbulence spectrum (Vanderhoeven, I., 1957)**

## EXPERIMENTAL METHOD

Figure 2 (below) shows the basic set-up. An array of 12 microphones was set on ground boards around the WTG. In addition to providing detailed information on noise radiation directivity, this eliminated the need to move microphones in response to changing wind direction. The yaw angle of the WTG nacelle was monitored via a potentiometer fitted at the top of the tower; thus the orientation of the microphone array with respect to the wind turbine could be determined at any time.

A 50m-high mast was set up 90m from the machine at a bearing of 320°, corresponding to the prevailing wind direction. Anemometers were fitted to the mast at heights of 10, 20, 30, 40 and 50m. Wind direction vanes were fitted at 10m, 30m, and 50m. Accelerometers were attached to the major mechanical noise sources: i.e. main bearing front footplate, nacelle bedplate, gearbox low-speed shaft, gearbox high-speed shaft, and generator. Two additional microphones were placed in the top of the tower and inside the nacelle in order to allow separation of structure-borne and airborne noise. All microphone signals were A-weighted in the pre-amplifiers to increase their signal-to-noise ratios. Two sets of optical tachos were fitted to the main rotor shaft to allow the instantaneous position of the rotor to be determined; one set produced a single pulse per revolution, the other eight pulses per revolution. Finally, a 10m mast was positioned between microphones 11 and 12 for the purpose of making hot-wire anemometer measurements of atmospheric turbulence.

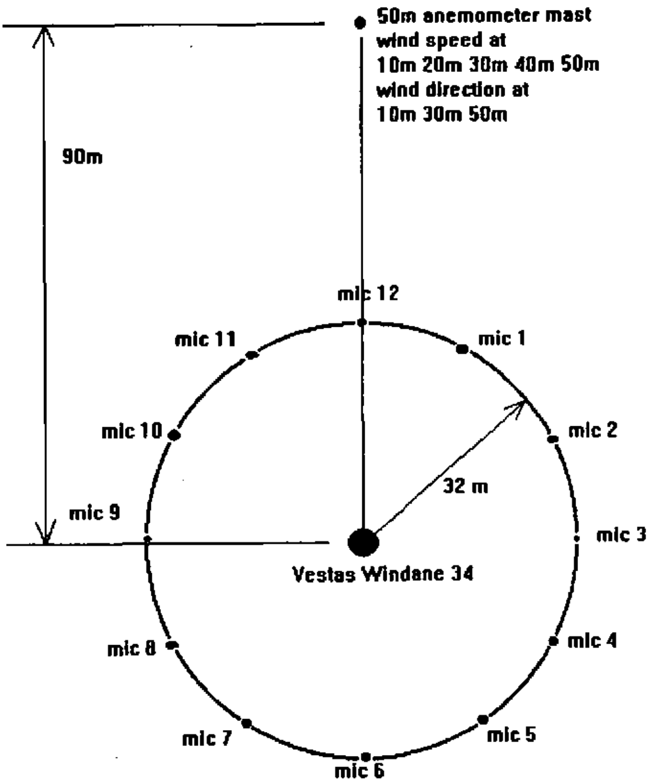


**Figure 2: basic experimental set-up**

## DATA ACQUISITION

A data acquisition system (DAQ) was specially designed and built to record the full range of necessary parameters. A Pentium PC fitted with multi-channel A/D converters was used to record directly to hard disk the wind speed and direction signals and the nacelle yaw angle. For all of these parameters the signals varied between 0 and 10V DC. Electrical power output and blade pitch information was obtained directly from the wind turbine control system via a serial-port connection, and also recorded directly to hard disk. A program was written in C to perform these operations automatically

Three synchronised digital tape recorders were used to record the signals from the 12 ground-based microphones, internal microphones and accelerometers and the timing pulses from the main rotor shaft. The tape recorder and hard-disk records were synchronised by the use of standard SMPTE time code which was output from the master tape recorder.

40 hours of multi-channel noise recordings were made on Vestas' Windane 34 machine at Coal Clough wind farm, UK, during July and August 1995. Background noise measurements (with the machine switched off) and white noise propagation tests were also performed.

## DATA SELECTION

The principal advantage of the current technique over previous multi-channel noise measurements lies in the fact that the key parameters (windspeed, yaw and power) are recorded directly to hard disk, and thus can easily be post-processed for desired test conditions, pinpointing sections of taped records where interesting noise data can be found.

The machine's hub height was 32m with a blade radius of 17.4m. Thus the top and bottom of the rotor disc were at heights of 49.4m and 14.6m respectively. To determine the effective wind across the rotor disc, the windspeeds at 20m, 30m, 40m, 50m were averaged together. The hard-disk records were then scanned to find instances when this effective hub-height wind speed was stable (i.e within +0.5m/s of a fixed speed) for more than 20 seconds.

It was found that the wind remained stable for at least 25% of the time, which was considerably more than expected. Instances of stable power output were also identified. Thus data was only selected for noise analysis if both wind conditions and machine power output were stable for more than 20 seconds. Furthermore, data was rejected unless the wind turbine axis was aligned within 5° of one of the microphones in the array. Of the 40 hours of data originally collected, only one hour satisfied all the above criteria of stability and accuracy. Analysis was further restricted to data in which the anemometers were upwind of the machine to within 60°, corresponding to current measurement standards, and to data towards the end of each stable period, to ensure that stable conditions detected at the mast had propagated to the turbine.

From analysis of hard-disk data, nineteen 10s periods conforming to all the above criteria were chosen to represent the most stable and accurate data possible. The noise recordings corresponding to these periods were isolated. For each selected period, a set of synchronous 10s time domain signals were prepared for each of the microphones, accelerometers and rotor sync pulses.

## RESULTS

The overall noise levels were calculated by averaging the sound pressure levels at all 12 microphones over the 10-second sample period. Figure 3 shows the average SPLs plotted as a function of machine electrical power output. All results are expressed as dBA relative to the sound pressure level measured at a 10m height wind speed of 8m/s, corresponding to the reference condition stipulated by the IEA technique.

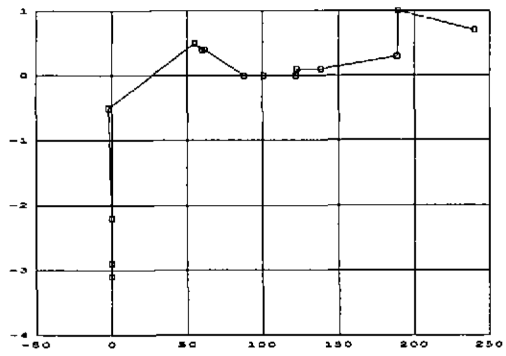


**Figure 3: noise (dBA) vs power (kW)**

Many pairs of points give identical noise levels at similar power outputs. This indicates that both the experimental method adopted here and wind turbine noise itself are highly repeatable.

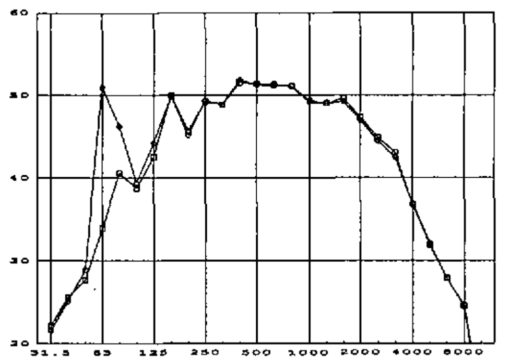


**Figure 4: two spectra at 10m/s, 190kW**

Only the two data points at 190kW (10m/s) differ noticeably in overall level under the same conditions. Downwind spectra for these two examples are plotted in figure 4. Although the two spectra are very similar, a large mechanical peak is present in one case at 63Hz, which accounts for the difference in level between the two examples.

It is significant that the measured SPL does not increase linearly with windspeed at the rate of 2dBA/m/s as has been determined using the IEA method (Odegaard & Danneskiold-Samsoe ApS 1991). Using the more accurate technique the overall SPL is actually higher at windspeeds between cut-in and the 8m/s IEA reference condition than at the reference condition itself.

Figure 5 (below) shows third-octave spectra up, down and cross-wind for the 100kW case. Broad-band noise levels are as much as 8dB lower in the 1-2kHz range in the plane of the rotor disc compared with the downwind case. This noise minimum in the plane of the disc is plainly audible in the field, but has not been fully revealed in any previous measurement.

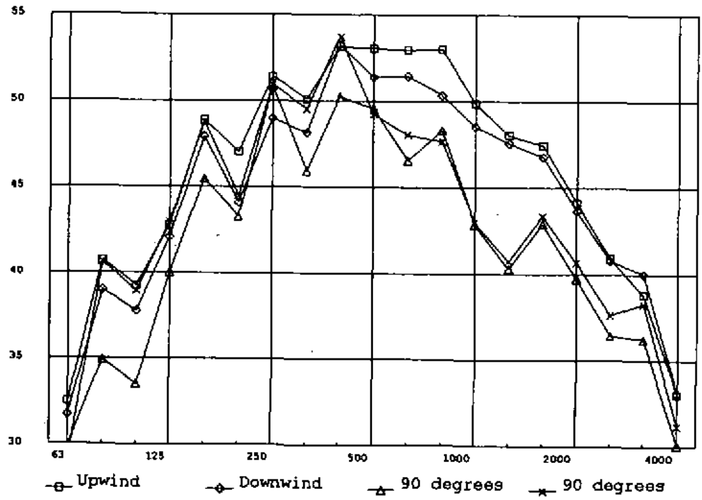


**Figure 5: noise directivity at 100kW**

## CONCLUSIONS

By restricting analysis to naturally occurring periods of steady wind, highly repeatable noise data can be obtained with respect to machine power output.

Power output is not well correlated with wind speed.

Noise can be higher at cut-in than at the 8m/s IEA reference condition.

More noise is radiated upwind than downwind.

An aerodynamic noise minimum exists in the plane of the rotor disc.

Comparison of measurements made using this technique cast doubt on the validity of the IEA method.

## ACKNOWLEDGEMENTS

This work was funded by ETSU, on behalf of the Department of Trade and Industry, as part of their new and renewable energy programme.

Thanks to project manager Andrew Bullmore of Hoare Lea and Partners, and Penny Dunbabin of Renewable Energy Systems.