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TECHNICAL NOTE

Combining Statistical Noise Levels and Application to Wind Farm Guidelines

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Abstract

It is stated in wind farm standards that logarithmic addition and subtraction of $L_{\mathrm{AF90},T}$ sound pressure levels is "not strictly mathematically correct". An analytical and experimental study reported in Tonin 2024 (a related article) examines the underlying accuracy of combining statistical noise levels as a general proposition, particularly the $L_{\mathrm{AF90},T}$ and the $L_{\mathrm{AF10},T}$. The objective of that study was to explore the accuracy of combining statistical noise levels and what might influence that accuracy. The objective of this study, as foreshadowed in Tonin 2024, is to apply the results to wind farms. It was concluded in Tonin 2024 that values of D_{90} (being the difference between the logarithmic sum and actual values of $L_{\mathrm{AF90},T}$) are negative in the range 0 to − 3 dB (for the cases in the study), meaning that the logarithmic sum of $L_{\mathrm{AF90},T}$ for the ambient and source sound pressure level distributions is less than the actual value of $L_{\mathrm{AF90},T}$ for the combined distribution. As a result, in deriving the wind farm noise level (as a contribution), the actual value of $L_{\mathrm{AF90},T}$ will be less than that determined by logarithmic subtraction of the individual components. In respect of the question of the underlying accuracy of combining statistical noise levels for wind farms, it is concluded that the difference between the logarithmic addition of the $L_{\mathrm{AF90},T}$ and the true value is less than 1 dB (for the cases in the study). The results are applied herein to a typical wind farm concluding that the simple energy subtraction method adopted in wind farm guidelines is conservative even allowing for the hypothesis that the fluctuation strength of wind farm noise is not invariant but increases with distance. It is also concluded that if wind farm guidelines were to assess wind farm noise on the basis of $L_{\mathrm{Aeq},T}$ rather than $L_{\mathrm{AF90},T}$ then adding a value of 2.5 dB to the derived wind farm noise level $L_{\mathrm{AF90},T}$ as currently specified in the guidelines (i.e., with $D_{90} = 0$ dB) would be conservative even allowing for the hypothesis that the fluctuation strength of wind farm noise is not invariant but increases with distance.

Keywords Ambient noise · Wind farm noise · Statistical noise levels · Logarithmic addition and subtraction of noise levels

1 Introduction

Ambient noise levels in an environment by their nature are not steady but vary with time as does any noise level for a source introduced into that environment. The level of variation in any noise sample is generally described in acoustics by statistical measures such as $L_{\mathrm{AF10},T}$ and $L_{\mathrm{AF90},T}$, which are defined as the A-weighted sound level (A) exceeded for 10% and 90% of the time, respectively, over measurement time interval T using the Fast time weighting (F), and the equivalent continuous sound pressure level $L_{\mathrm{Aeq},T}$ defined as [1]:

$$L_{\mathrm{Aeq},\,T} = 10\log\frac{1}{T}\int_0^T \frac{p_A^2(t)}{p_0^2}\mathrm{d}t\ \mathrm{d}B \tag{1}$$

where $p_A(t)$ is the instantaneous A-weighted pressure (Pa), T is the measurement time interval (seconds) and p_0 is the reference pressure 20 μPa.

It is often necessary to calculate the combined total equivalent continuous sound pressure level at a receptor location when a new source is brought into operation at a nearby site, which is determined according to the following formula:

$$L_{\mathrm{Total}} = 10\log(10^{\frac{L_{\mathrm{amb}}}{10}} + 10^{\frac{L_{\mathrm{source}}}{10}}) \tag{2}$$

where L_{amb} is the $L_{\mathrm{Aeq},T}$ of the ambient at the receptor location without the new source operating, L_{source} is the $L_{\mathrm{Aeq},T}$ of the new source contribution and L_{Total} is the combined total

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$L_{\mathrm{Aeq},T}$ sound pressure level with the new source operating. This formula applies when the two sounds are incoherent [2].

Similarly, there are occasions when it is required to determine the sound pressure level contribution of a source, where the underlying ambient sound pressure level is subtracted from the measured combined total sound pressure level. Equation (2) therefore becomes [3]:

$$L_{\mathrm{source}} = 10\log(10^{\frac{L_{\mathrm{Total}}}{10}} - 10^{\frac{L_{\mathrm{amb}}}{10}}) \quad (3)$$

wherein the sound levels are represented by the equivalent continuous sound pressure level $L_{\mathrm{Aeq},T}$.

Noise from wind farms in Australia and in the UK are measured using the $L_{\mathrm{AF90,10\ min}}$ descriptor for both the background ambient noise (without the wind farm operating) and when the wind farm is operating as recommended in the report of the Noise Working Group engaged by the Energy Technology Support Unit (ETSU) at the UK Department of Trade and Industry in 1996, otherwise known as ETSU-R-97 [4]. The claimed reason the $L_{\mathrm{AF90,10\ min}}$ descriptor is used for wind farms is that noise from wind turbines is relatively steady and constant in level as opposed to other industrial or commercial noise sources; and therefore, the contribution of noise from a wind farm is more relevantly assessed having regard to the average minimum of the total measured noise level as represented by the $L_{\mathrm{AF90,10\ min}}$ descriptor. The methodology adopted is to measure the $L_{\mathrm{AF90,10\ min}}$ background sound pressure level at a receptor location without the wind farm operating and the $L_{\mathrm{AF90,10\ min}}$ background sound pressure level at another time when the wind farm is operating, coordinated with the hub height wind speed measured at the turbines, using Eq. (3) to arrive at the contributing $L_{\mathrm{AF90,10\ min}}$ sound pressure level from the wind farm despite the fact that Eq. (3) applies only to the $L_{\mathrm{Aeq},T}$. The ETSU report states that[1]:

> It is recognized that the correction method above only strictly applies to the correction of one Lcq by another. Readers are referred to the paper by Nelson [reference omitted] for more discussion on correcting percentile measurements.

A similar comment is made in New Zealand Standard NZS 6808:2010 which is commonly used in Australia and New Zealand [5]:

> 7.5.3 Post-installation measurements will capture both the wind farm sound and the background sound. In order to assess the wind farm sound level alone, the contribution of the background sound shall be removed from the regression curve drawn in 7.5.2 at each integer wind speed.
>
> C7.5.3 While a simple energy subtraction of background and post-installation sound levels is not strictly mathematically correct for L90 centile levels, the difference may be taken as the L90 wind farm sound levels.

and the method is also adopted in the South Australian guidelines [6]. The Queensland draft guidelines [7] states that "the L_{A90} descriptor is used as a proxy for the L_{Aeq} for the purposes of noise monitoring", however this does not avoid the issue. These standards and guidelines will collectively be referred to as "guidelines" from hereon.

In Tonin 2024 [8] an analytical study is described involving the logarithmic addition of random noise samples using the Monte Carlo method which involves repeated random sampling. The Monte Carlo method is a simulation of a random process whereby random numbers of the simulated variables are generated and combined according to underlying physical formulas. The analytical study was supplemented by an experimental study involving the analysis of several audio files, both separately and electronically mixed, to simulate measurements one would obtain in practice.

The results of Tonin 2024 are applied herein to a typical wind farm, in respect of deriving the wind farm noise level as a contribution, as proposed in the guidelines discussed above.

2 Analytical Study

Consider two A-weighted sound pressure distributions $p_{A1}(t)$ and $p_{A2}(t)$ as measured by the microphone of a sound level meter. The total sound pressure is:

$$p_{\mathrm{A}}(t) = p_{\mathrm{A1}}(t) + p_{\mathrm{A2}}(t) \quad (4)$$

and therefore,

$$p_{\mathrm{A}}^2(t) = p_{\mathrm{A1}}^2(t) + p_{\mathrm{A2}}^2(t) + 2p_{\mathrm{A1}}(t)p_{\mathrm{A2}}(t) \quad (5)$$

If $p_{\mathrm{A1}}(t)$ and $p_{\mathrm{A2}}(t)$ are uncorrelated then the total A-weighted mean square pressure $< p_{\mathrm{AF}}^2(t) >$ is (where the brackets $\langle\,\rangle$ denote an average value determined at time t using the F fast time weighting):

$$< p_{\mathrm{AF}}^2(t) > = < p_{\mathrm{AF1}}^2(t) > + < p_{\mathrm{AF2}}^2(t) > \quad (6)$$

because the third term $< 2p_{\mathrm{A1}}(t)p_{\mathrm{A2}}(t) >$ reduces to zero [2]. Therefore, using Eq. (6), the total sound pressure level is:

$$L_{\mathrm{AF}}(t) = 10\log(10^{\frac{L_{\mathrm{AF1}}(t)}{10}} + 10^{\frac{L_{\mathrm{AF2}}(t)}{10}}) \quad (7)$$

The extent of spread or fluctuation range of the temporal variation of the sound pressure levels $L_{\mathrm{AF}}(t)$, $L_{\mathrm{AF1}}(t)$ and

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[1] Page 88 reference [4].

$L_{\mathrm{AF2}}(t)$ is indicated by their probability density functions (PDF). In Tonin 2024, examples of the PDF for a range of noise sources and ambient locations are shown, none having a strict Gaussian shape (even though some come close).

The analytical study in Tonin 2024 involves the combination of Gaussian distributions of sound pressure levels because this represents a simple case to model mathematically using the Monte Carlo method in the absence of a closed form solution. As previously stated, the Monte Carlo method is a simulation of a random process whereby random numbers of the simulated variables are generated and combined according to underlying physical formulas. The analytical study assumes that the PDFs of the sound pressure level distributions are Gaussian of the form:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} \tag{8}$$

where σ is the standard deviation of the sound pressure level and μ is the mean.

The total sound pressure level distribution $L_{\mathrm{AF}}(t)$ was derived in Tonin 2024 using the Monte Carlo method in Microsoft Excel. The 10th and 90th percentiles of a distribution, denoted as $L_{\mathrm{AF10},T}$ and $L_{\mathrm{AF90},T}$, are the levels exceeded for 10% of the time and 90% of the time, respectively. An incremental time difference of $\Delta t = 100$ ms over a time interval $T = 600$ secs was used in the analysis because an interval of 10 min is invariably adopted in the guidelines.

The difference D_{90} between the logarithmic sum of the $L_{\mathrm{AF90},T}$ for the sound pressure level distributions $L_{\mathrm{AF1}}(t)$ and $L_{\mathrm{AF2}}(t)$ and the $L_{\mathrm{AF90},T}$ for the combined simulated distribution $L_{\mathrm{AF}}(t)$ (i.e., the true result) is defined as:

$$D_{90} = L_{\mathrm{AF90},\,T}(\mathrm{LogarithmicSum}) - L_{\mathrm{AF90},\,T}(\mathrm{Simulated})\mathrm{dB} \tag{9}$$

where "Logarithmic Sum" means the logarithmic sum in Eq. (7).

In Tonin 2024, it is shown that the "fluctuation strength" (defined as the difference $L_{\mathrm{AF10},T}$–$L_{\mathrm{AF90},T}$ as displayed on a sound level meter) is a factor affecting the outcome of combining statistical noise levels. Figure 1 shows the analytical values of D_{90}, represented as lines, for a Gaussian distribution.

In Fig. 1, the analytical results for a Gaussian distribution are shown as black lines for the case where the fluctuation strength of the ambient "Amb" equals 5, 10 and 15 dB, respectively. These are plotted against the fluctuation strength of the source with a range 0–18 dB. The value for D_{90} is negative meaning that the logarithmic sum of the $L_{\mathrm{AF90,T}}$ for the ambient and source results in a value which is less than the combined simulated true value.

It was concluded in Tonin 2024 that:

1. The difference D_{90} is negative in the range 0 to − 3 dB (for the cases in the study), where D_{90} is the difference between the logarithmic sum of $L_{\mathrm{AF90},T}$ for the ambient and source sound pressure level distributions and the actual value of $L_{\mathrm{AF90},T}$ for the combined distribution. Put another way, the logarithmic sum $L_{\mathrm{AF90},T}$ of the two sound pressure level distributions is less than the $L_{\mathrm{AF90},T}$ for the combined distribution and therefore underpredicts the value;
2. The difference D_{90} is not substantially affected (within about 0.7 dB) by the relative difference in the $L_{\mathrm{AF90},T}$ of the two sound pressure level distributions. An analysis was conducted with the source $L_{\mathrm{AF90},T}$ set at a level of − 5, 0 and + 5 dB with respect to the $L_{\mathrm{AF90},T}$ of the ambient; and,
3. The difference D_{90} increases (i.e., becomes more negative) with increasing fluctuation strength of either distribution.

The conclusions apply to sound pressure level distributions having a Gaussian distribution. In the next section, a summary of an experimental study is presented, combining sound pressure level distributions which are not Gaussian, as measured in real situations.

3 Experimental Study

This section is a summary of the experimental study in Tonin 2024 involving the combination of statistical noise levels using audio data recorded in real situations for a variety of noise sources including six wind turbine types, a resource recovery industrial site, patron noise in a beer garden and wedding setting, and a construction site. Noise recordings of these sources are combined with recordings from eleven ambient situations including rural, suburban and urban locations. Values of $L_{\mathrm{AF10},T}$ and $L_{\mathrm{AF90},T}$ for the uncombined audio samples, for the combined audio samples and the corresponding differences D_{90} are determined and compared with the corresponding values determined for a Gaussian distribution as outlined in the previous section.

Pertinent to this study, audio recordings of the six wind turbines were selected from a compendium of 31 wind turbines supplied with ISO/TS 20065:2022 [9]. A description of the audio recordings is provided in Sondergaard 2019 [10]. The audio recordings were obtained from noise measurements conducted close to the subject wind turbines in accordance with IEC 61400-11 [11]. The distances from sound level meter to turbine are not stated but the standard specifies the reference distance should be the hub height plus one-half of the rotor diameter (e.g. 150 m for a hub height of 90 m and rotor blade length of 60 m). As stated in Sondergaard 2019, the recordings were made with a Class 1 sound level meter

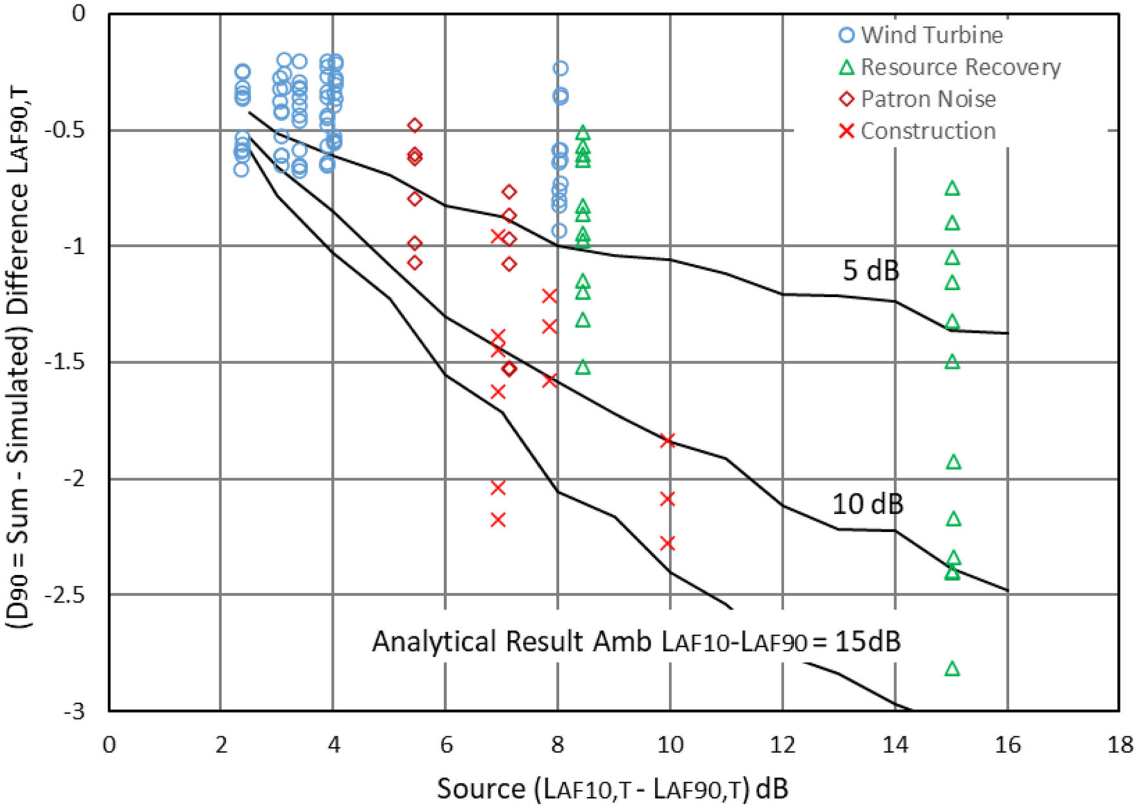

Fig. 1 Experimental values of D_{90} compared with the analytical result for a Gaussian distribution (ref Tonin 2024)

with a sample duration of 20 s. The 20 s audio recordings were concatenated to produce an audio signal of the required length to match that of the ambient recording.

The wind turbine audio recordings were combined with ambient noise recorded at five rural locations at different times of the day, evening and night. The first location is in a rural area and was selected for study because it is within 2 km of an existing wind farm. The principal noise sources are wind in the trees, bird sounds and the occasional passing motor vehicle. All audio recordings were made when the wind turbines were non-operational. The equipment used for recordings was a 01 dB CUBE Class 1 sound level meter. Each audio recording has a duration of 120 s. The fluctuation strength of the ambient is in the range 1.8–18.1 dB.

The remaining four locations are in a rural area proximate to each other but not adjacent to a wind farm. Again, the principal noise sources are wind in the trees, distant traffic and bird and land-based fowl sounds. The equipment used for recordings was an NTi XL2 Class 1 sound level meter. Each audio recording has a duration of 600 s. The fluctuation strength of the ambient is in the range 5.2–20.1 dB.

All audio samples were recorded as WAV files with varying sampling frequencies, some with audio compression and some without, however, as the identical audio samples are analyzed on their own or in combination with the other audio samples and it is the difference between the former and the latter that is of interest, any distortion in the originally recorded data are not relevant.

The audio WAV samples are uploaded to Audacity, a digital audio editor and recording application software. The WAV samples are converted using Audacity to a sampling frequency of 44.1–48 kHz, the respective source and ambient samples are mixed at predefined levels and the resulting sound pressure levels measured using noiseLAB Pro software. A check of the accuracy of the gain adjustments in Audacity and the corresponding measurement in noiseLAB Pro reveals the process produces consistent results within 0.02 dB.

The experimental results are shown in Fig. 1 as single data points for all the sources considered in Tonin 2024. As the experimental noise source and ambient are non-Gaussian distributions, one cannot expect a one-to-one correspondence with the analytical Gaussian results shown as solid lines. The best one is able to infer from Fig. 1 is that the experimental results are in the range consistent with the theoretical analysis of a Gaussian distribution. In particular, the trend is clear (as expected) that low values of fluctuation strengths in both the ambient and source produce values of D_{90} tending closer to 0 dB.

4 Discussion

It is clear from Fig. 1 that there is no practical situation where $D_{90} = 0$ dB and that the value of D_{90} depends upon the fluctuation strength of both the ambient sound pressure level and the source sound pressure level. As expected, a lower fluctuation strength in general results in a value of D_{90} closer to zero. For example, one may conclude as a worst case that provided the fluctuation strength of the ambient (black line) is not greater than 5 dB and the fluctuation strength in the source (absicca) is not greater than about 8 dB then the magnitude of D_{90} is less than 1 dB (for the cases in the study).

Relevantly, all the wind turbine noise sources examined in the study have a magnitude of D_{90} less than 1 dB. In respect of the question of the underlying accuracy of combining statistical noise levels for wind farms, it is therefore concluded that the difference between the logarithmic addition of the $L_{\mathrm{AF90},T}$ and the true value is less than 1 dB.

The consequence of the observation that D_{90} is always negative depends upon the application. For example, if one is interested in estimating the total combined sound pressure level $L_{\mathrm{AF90},T}$ Total by summing the individual contributions of ambient and source then, combining Eq. (2) with Eq. (9) results in the following:

$$L_{\mathrm{AF90},\,T\mathrm{Total}} = 10\log(10^{\frac{L_{\mathrm{AF90},\,T\mathrm{amb}}}{10}} + 10^{\frac{L_{\mathrm{AF90},\,T\mathrm{source}}}{10}}) - D_{90} \tag{10}$$

and therefore the estimate for $L_{\mathrm{AF90},T}$ Total will be greater than the logarithmic summation of the individual components.

On the other hand, if one is interested in determining the $L_{\mathrm{AF90},T}$ of the source contribution in the total combined sound pressure level $L_{\mathrm{AF90},T}$ Total, then Eq. (3) becomes:

$$L_{\mathrm{AF90},\,T\mathrm{source}} = 10\log(10^{\frac{L_{\mathrm{AF90},\,T\mathrm{Total}}+D_{90}}{10}} - 10^{\frac{L_{\mathrm{LAF90},\,T\mathrm{amb}}}{10}}) \tag{11}$$

In this case, the estimate for $L_{\mathrm{AF90},T}$ source will be less than the logarithmic subtraction of the individual components.

5 Application to Wind Farm Standards and Guidelines

The results of the previous sections are now applied to the assessment of noise from a typical wind farm. In Australia, as previously stated, wind farm guidelines differ between the states with NZS 6808:2010 [5] adopted in Victoria, the SA guidelines [6] adopted in South Australia and New South Wales (with modifications) and State code 23 adopted in Queensland [7]. In the United Kingdom, ETSU-R-97 [4] is recommended by the Institute of Acoustics [12].

The methodology for assessing wind farm noise levels is similar in each of the guidelines. A measurement survey is conducted at each noise sensitive receiver prior to the wind farm becoming operational. This results in a set of $L_{\mathrm{A90,10\,min}}$ noise levels correlated with hub height wind speeds as shown in Fig. 2 as green circles. A regression line with a specified polynomial order (shown as a solid line in the figure) is then calculated for the data, representing the mean value of $L_{\mathrm{A90,10\,min}}$, denoted as “Poly”.

Also shown in Fig. 2 as brown circles are the corresponding values of fluctuation strength $L_{\mathrm{A10,10\,min}}$–$L_{\mathrm{A90,10\,min}}$ together with a dotted regression line. The fluctuation strength data are not referred to in the guidelines and is therefore omitted in environmental assessments.

Figure 3 shows the corresponding post-construction noise levels at the same receiver location, but in this case all wind turbines are operational. The blue circles are the measured $L_{\mathrm{A90,10\,min}}$ noise levels correlated with hub height wind speed, with the polynomial regression line shown in black. The red circles are the corresponding values of fluctuation strength $L_{\mathrm{A10,10\,min}}$–$L_{\mathrm{A90,10\,min}}$ together with a dotted regression line.

It is noted that in both the pre- and post-construction the fluctuation strength varies, with most of the data values being below 20 dB and with an average value of approximately 10 dB.

Pursuant to the guidelines, the $L_{\mathrm{A90,10\,min}}$ noise levels at integer wind speeds derived from the pre-construction regression line are logarithmically subtracted from the corresponding post-construction values using Eq. (3) to obtain the derived wind farm noise level (that is, the contributing noise level from the wind farm without the contribution of the ambient noise level). Figure 4 shows the result using the data in Figs. 2 and 3. While every wind farm assessment is unique, Fig. 4 is typical for a wind farm, with a similar result, for example, being depicted in Fig. 5 of reference [7].

The derived wind farm noise level is to be compared with the specified noise criteria in the applicable wind farm guideline to demonstrate compliance (the typical requirement being that the derived wind farm noise level shall not exceed the pre-construction $L_{\mathrm{A90,10\,min}}$ regression line by more than 5 dB with a minimum threshold of 35–40 dB).

The use of Eq. (3) as specified in the guidelines to derive the wind farm noise level assumes a value for $D_{90} = 0$ dB in Eq. (11). Reference to Fig. 1 shows that the measured values for D_{90} are on average −0.5 dB for the wind turbines the subject of this study which, when inserted in Eq. (11), results in a revised estimate for the derived wind farm noise level shown as a dotted line in Fig. 5 (immediately below the solid line).

As is evident in Fig. 1, the value of D_{90} is dependent upon the fluctuation strength of both the source (in this case the wind turbines) and the ambient. As previously stated,

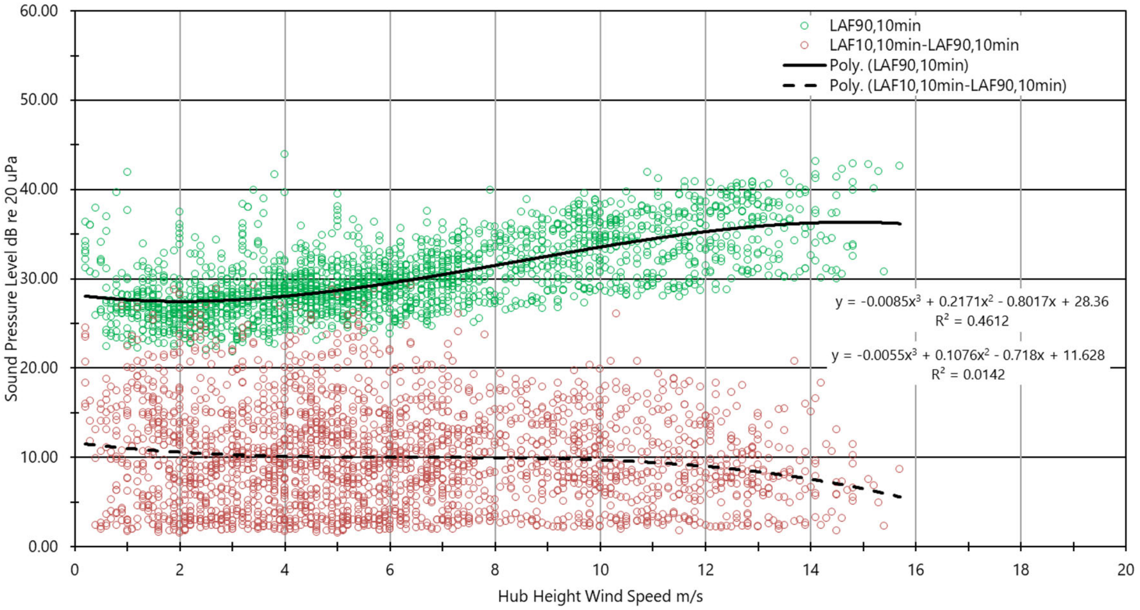

Fig. 2 Pre-construction $L_{\mathrm{A90,10\,min}}$ noise levels and fluctuation strength ($L_{\mathrm{A10,10\,min}}$–$L_{\mathrm{A90,10\,min}}$) for a typical wind farm correlated with hub height wind speed

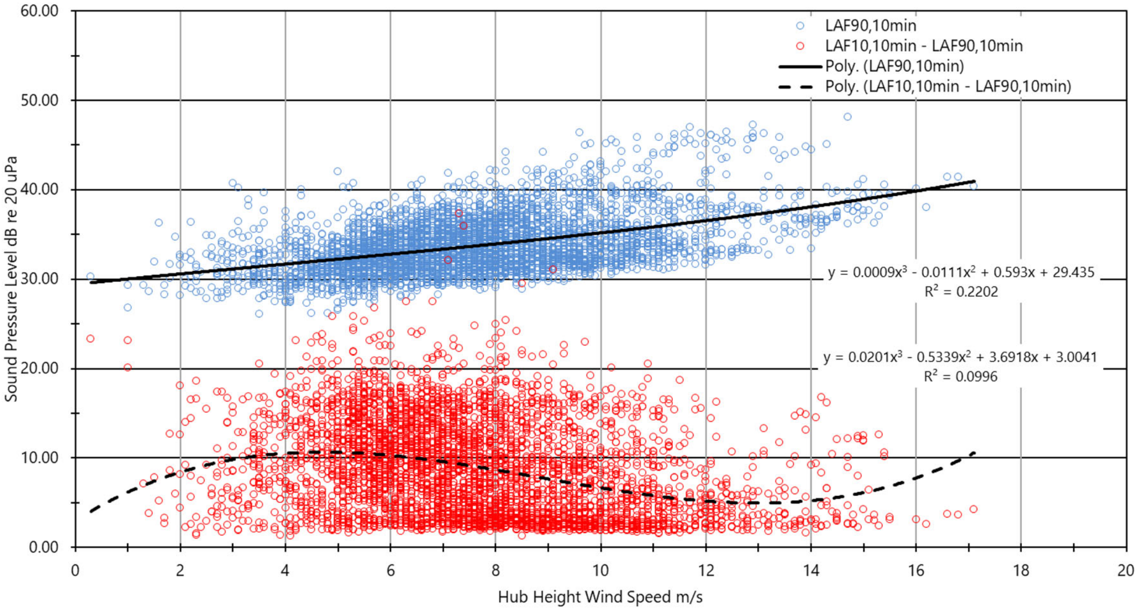

Fig. 3 Post-construction $L_{\mathrm{A90,10\,min}}$ noise levels and fluctuation strength ($L_{\mathrm{A10,10\,min}}$–$L_{\mathrm{A90,10\,min}}$) for a typical wind farm correlated with hub height wind speed

the fluctuation strength of the wind turbines was measured approximately 150 m from the wind turbines. Assuming the fluctuation strength of the ambient is dependent upon local conditions (such as vegetation and anthropogenic noise sources) rather than related to the separation distance from the wind turbines, the question is whether the fluctuation strength of the wind turbines varies with distance from the wind turbines.

There appears to be no material evidence in the literature relating to this issue (and quite rightly it would be difficult to measure) but it has been raised by Hansen 2017 [13] stating:

> Many regulations for wind farm noise are written in terms of an L_{A90} level, which is the A-weighted sound level that is exceeded 90% of the time. The idea of this approach is that wind farm noise is supposedly relatively steady; whereas, background noise fluctuates

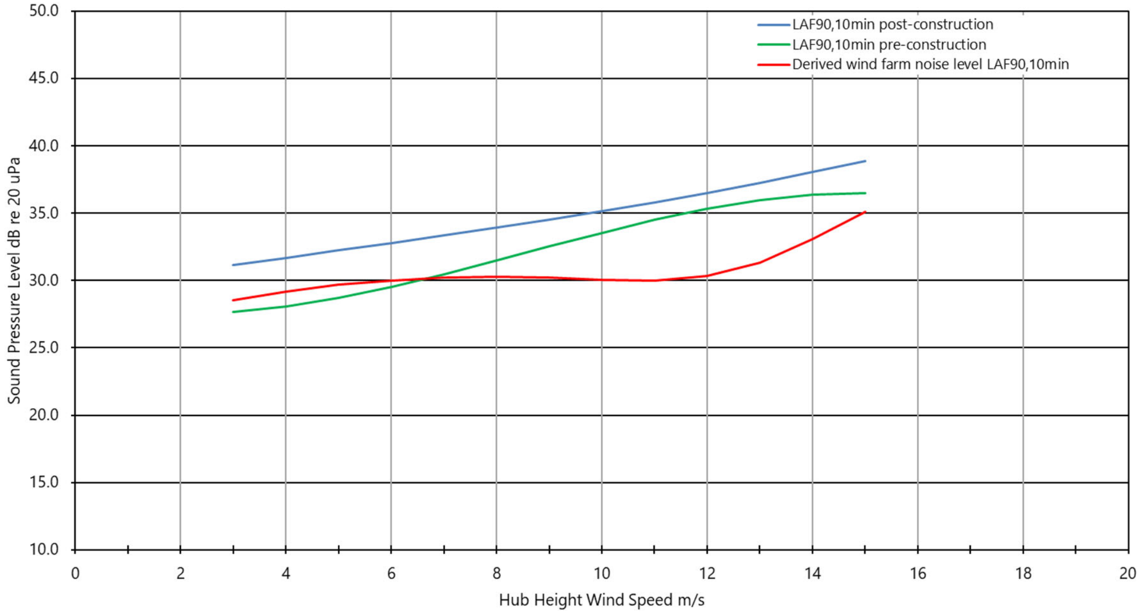

Fig. 4 Derived wind farm noise level obtained by logarithmic subtraction of pre- from post-construction noise levels correlated with hub height wind speed

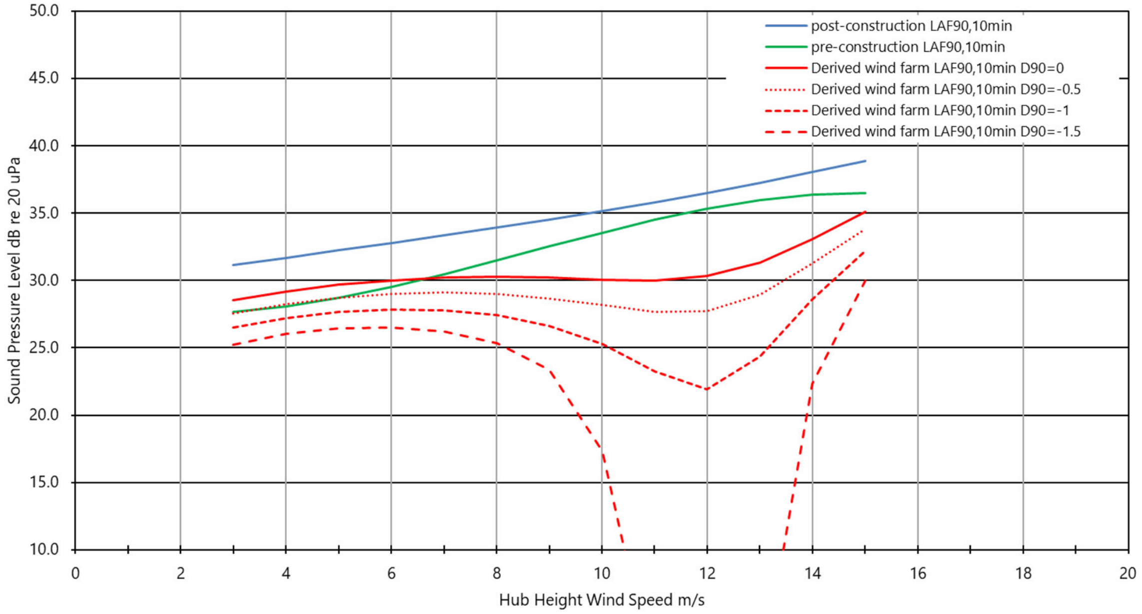

Fig. 5 Derived wind farm noise level $L_{\mathrm{AF90,10\,min}}$ for a range of D_{90} values correlated with hub height wind speed

considerably. So the idea is that an L_{A90} measurement will remove most of the background noise and just measure the wind farm noise. Of course this is an erroneous assumption because wind farm noise fluctuates wildly at residential locations more than a few hundred meters distant as a result of varying atmospheric conditions affecting both the generation and propagation of the noise. Use of an L_{A90} measurement effectively ignores the worst 90% of wind farm noise. A more useful descriptor would be an L_{A50} measurement, which is the noise level that is exceeded 50% of the time.[2]

The first issue raised in Hansen 2017 is that the fluctuation strength of wind farm noise increases with distance due to varying atmospheric conditions affecting both the generation and propagation of noise, noting that, in practice, the

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[2] Hansen 2017 page 75.

Table 1 Wind turbine fluctuation strength $L_{\mathrm{AF10},T}$–$L_{\mathrm{AF90},T}$ and $L_{\mathrm{Aeq},T}$–$L_{\mathrm{AF90},T}$ as a function of D90

D_{90} dB	Fluctuation strength $L_{\mathrm{AF10},T}$–$L_{\mathrm{AF90},T}$ dB	$L_{\mathrm{Aeq},T}$–$L_{\mathrm{AF90},T}$ dB
– 0.5	4.1	2.18
– 1	6.9	4.0
– 1.5	9.8	5.6

distance of residential receivers from wind farms is usually more than 1 km. If the hypothesis in Hansen 2017 is adopted, that the fluctuation strength of the wind turbines increases with distance then, as evident in Fig. 1, the value of D_{90} would become more negative. Therefore, the derived wind farm noise levels would be even lower as shown in Fig. 5 by the additional dashed lines, for the case of D_{90} being equal to – 1 dB and – 1.5 dB, for example.

The first and second columns in Table 1 show the corresponding fluctuation strengths for the wind turbines under study for values of D_{90} equal to – 0.5, – 1 and – 1.5 dB. The fluctuation strength in the first row (i.e., $D_{90} = -0.5$ dB) is the arithmetic mean of the measured data for the six turbines. The fluctuation strength for the second and third rows is calculated from the slope of the line in Fig. 1 for the case of the ambient $L_{\mathrm{AF10},T}$–$L_{\mathrm{AF90},T} = 10$ dB (which is representative of the fluctuation strength of the ambient).

Figure 5 shows that even if the fluctuation strength of wind turbine noise increases with distance (resulting in greater values of D_{90}, meaning more negative), then the derived $L_{\mathrm{AF90},T}$ wind turbine noise levels would decrease accordingly, compared with the simple energy subtraction method (i.e., with $D_{90} = 0$ dB) used in the guidelines. It is therefore concluded that the simple energy subtraction method adopted in the guidelines is conservative even allowing for the hypothesis that the fluctuation strength of wind farm noise is not invariant but increases with distance.

The second issue raised in Hansen 2017 is that the $L_{\mathrm{AF90},T}$ is an inappropriate measure of wind turbine noise and instead the $L_{\mathrm{AF50},T}$ metric should be used. ETSU-R-97 gives the following reason for adopting the $L_{\mathrm{AF90},T}$ for assessing turbine noise[3]:

> The use of L_{A90} was proposed by some local district councils in Cornwall because transitory, high-energy effects such as aircraft flyovers and wind upon the microphone could increase the measured L_{Aeq} such that the measured noise levels from the turbines would be masked. As a wind turbine is a fairly constant noise source it was considered that the L_{A90} would be a reasonable approximation to the L_{Aeq} of a wind turbine. However, at a receiver position, where short-term, high-energy events may result in a higher L_{Aeq} than would be expected from just the operation of wind turbines, the L_{A90} was considered to be less affected by these transitory, high-energy events.

This reasoning would also apply to the $L_{\mathrm{AF50},T}$ metric should it be used as advocated by Hansen 2017. There appears to be no valid reason for adopting a new statistical metric when the $L_{\mathrm{Aeq},T}$ is universally adopted for assessing noise impact from industry and wind farms (ISO 1996-2 [1], World Health Organization [14]). ETSU-R-97 acknowledges the following about the $L_{\mathrm{Aeq},T}$ noise level[4]:

> In summary, the Noise Working Group is agreed that the $L_{\mathrm{A90,10min}}$ descriptor should be used for both the background noise and the wind farm noise and that when setting limits it should be borne in mind that the $L_{\mathrm{A90,10min}}$ of the wind farm is likely to be about 1.5–2.5 dB(A) less than the L_{Aeq} measured over the same period.

If the $L_{\mathrm{Aeq},T}$ noise metric were to be adopted instead of the $L_{\mathrm{AF90},T}$ for noise assessment purposes, then one would need to examine how the $L_{\mathrm{Aeq},T}$ varies with values of D_{90}.

The range of 1.5–2.5 dB quoted above in relation to the difference $L_{\mathrm{Aeq},T}$–$L_{\mathrm{AF90},T}$ is consistent with the measured mean level of 2.18 dB obtained for the wind turbines in this study as evident in the first row third column of Table 1. But if the fluctuation strength were to increase with distance as postulated by Hansen 2017 then the difference $L_{\mathrm{Aeq},T}$–$L_{\mathrm{AF90},T}$ would also increase accordingly. The data for the six wind turbines in this study shows that the ratio $(L_{\mathrm{Aeq},T}–L_{\mathrm{AF90},T})/(L_{\mathrm{A10},T}–L_{\mathrm{AF90},T})$ has a mean of 0.54 (range 0.51–0.57), and therefore the corresponding values of $L_{\mathrm{Aeq},T}$–$L_{\mathrm{AF90},T}$ in the third column of Table 1 can be derived for the other values of D_{90} assuming the ratio is constant.

In other words, if it is assumed the fluctuation strength increases with distance, resulting in a lower $L_{\mathrm{AF90},T}$ for the derived wind farm noise level as shown in Fig. 5, there would be a corresponding increase in the $L_{\mathrm{Aeq},T}$ offsetting this effect. This is demonstrated in Fig. 6 where the difference $L_{\mathrm{Aeq},T}$–$L_{\mathrm{AF90},T}$ is added to the values in Fig. 5 to arrive at the $L_{\mathrm{Aeq,10\ min}}$ noise levels.

In Fig. 6, the derived wind farm $L_{\mathrm{Aeq,10\ min}}$ (the dashed blue curves) are compared with the derived wind farm $L_{\mathrm{AF90,10\ min}}$ with $D_{90} = 0$ dB (the red solid curve) required in the guidelines. The maximum positive differences above the red solid curve are in the range 1.3–2.1 dB. It is therefore concluded that if wind farm guidelines were to assess wind farm noise on the basis of $L_{\mathrm{Aeq},T}$ rather than $L_{\mathrm{AF90},T}$, then adding a value of 2.5 dB to the derived wind farm noise level

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[3] Page 16 ETSU-R-97 [4].

[4] Page 58 *ibid.*

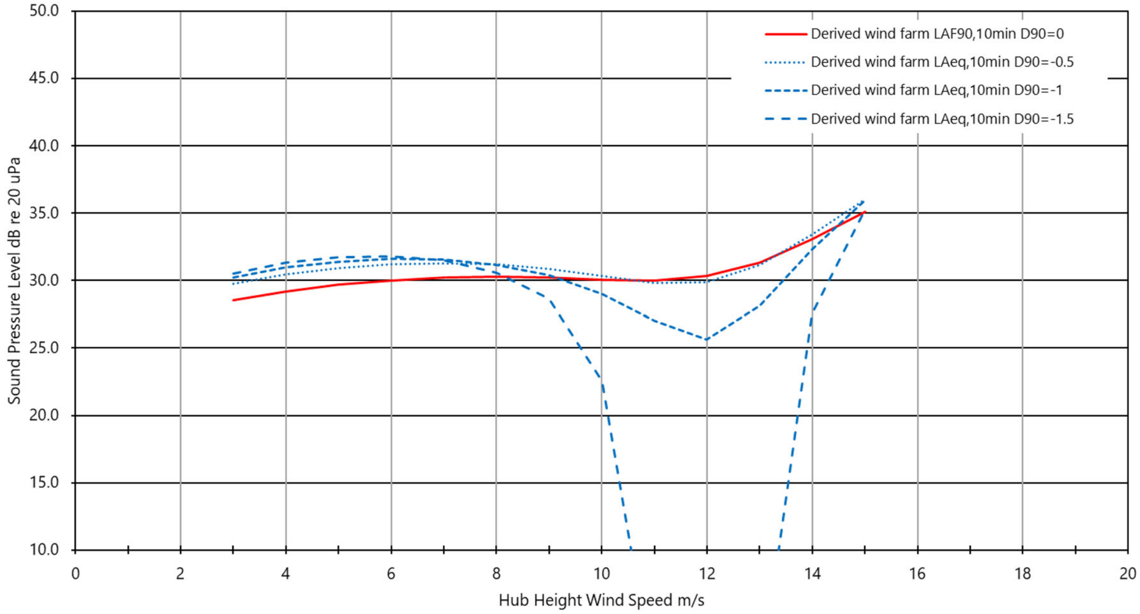

Fig. 6 Derived windfarm $L_{\mathrm{Aeq,10\,min}}$ noise levels for a range of D_{90} values correlated with hub height wind speed

$L_{\mathrm{AF90},T}$ as currently specified in the guidelines (i.e., with $D_{90} = 0$ dB) would be conservative even allowing for the hypothesis that the fluctuation strength of wind farm noise is not invariant but increases with distance.

6 Conclusion

Combining values of $L_{\mathrm{AF90},T}$ is important in the wind energy industry particularly where the contribution from wind turbines is to be determined from the total measured noise level. It is stated in wind farm standards and guidelines that logarithmic addition and subtraction of $L_{\mathrm{AF90},T}$ sound pressure levels is *"not strictly mathematically correct"*, and therefore the objective of this study is to explore the accuracy of the results and what might influence the accuracy.

The analytical study in Tonin 2024 involves the combination of Gaussian distributions of sound pressure levels because this represents a simple case to model mathematically using the Monte Carlo method in the absence of a closed form solution.

The experimental study in Tonin 2024 uses audio data recorded in real situations. The sources of noise include six wind turbine types, a resource recovery industrial site, patron noise in a beer garden and wedding setting, and a construction site. Noise recordings from these sources are combined with recordings from eleven ambient situations including rural, suburban and urban locations.

The conclusions of the Tonin 2024 study are as follows:

1. The difference D_{90} is negative in the range 0 to − 3 dB (for the cases in the study), where D_{90} is the difference between the logarithmic sum of $L_{\mathrm{AF90},T}$ for the ambient and source sound pressure level distributions and the actual value of $L_{\mathrm{AF90},T}$ for the combined distribution. Put another way, the logarithmic sum $L_{\mathrm{AF90},T}$ of the two sound pressure level distributions is less than the $L_{\mathrm{AF90},T}$ for the combined distribution and therefore underpredicts the value;
2. The difference D_{90} is not substantially affected (within about 0.7 dB) by the relative difference in the $L_{\mathrm{AF90},T}$ of the two sound pressure level distributions; and,
3. The difference D_{90} increases (i.e., becomes more negative) with increasing fluctuation strength of either distribution.

The consequence of the observation that D_{90} is always negative depends upon the application. For example, if one is interested in estimating the total $L_{\mathrm{AF90},T}$ by summing the individual contributions of ambient and source then the actual value of $L_{\mathrm{AF90},T}$ will be greater than the logarithmic summation of the individual components. On the other hand, if one is interested in determining the source contribution in the total measured sound pressure level, then the value of $L_{\mathrm{AF90},T}$ for the source will be less than the logarithmic subtraction of the individual components.

In respect of the question of the underlying accuracy of combining statistical noise levels for wind farms, it is concluded that the difference between the logarithmic addition of the $L_{\mathrm{AF90},T}$ and the true value is less than 1 dB (for the cases in the study).

The application of these results to a typical wind farm shows that the simple energy subtraction method adopted in the guidelines is conservative even allowing for the hypothesis that the fluctuation strength of wind farm noise is not invariant but increases with distance.

It is also concluded that if wind farm guidelines were to assess wind farm noise on the basis of $L_{\mathrm{Aeq},T}$ rather than $L_{\mathrm{AF90},T}$, then adding a value of 2.5 dB to the derived wind farm noise level $L_{\mathrm{AF90},T}$ as currently specified in the guidelines (i.e., with $D_{90} = 0$ dB) would be conservative even allowing for the hypothesis that the fluctuation strength of wind farm noise is not invariant but increases with distance.

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