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# Technical Note

# Corrected Long-Term Time-Average Sound Level of Amplitude-Modulated Wind Turbine Noise

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Amplitude-modulated noise from a single wind turbine is considered. The time-varying modulation depth $D_m$ and the short time-average sound level $L_{\mathrm{Aeq},\tau}$ (with $\tau$ = 20 s) are measured at the reference distance $d_*$. Due to amplitude modulation, a penalty has to be added to $L_{\mathrm{Aeq},\tau}$. The paper shows how to calculate the corrected long-term time-average sound level $\widehat{L}_{\mathrm{Aeq},T}$ (with $T \gg 20$ s), which accounts for amplitude modulation at any distance $d \neq d_*$ from the wind turbine. The proposed methodology needs to be tested by research.

**Keywords:** wind turbine noise; amplitude modulation; annoyance.



## 1. Introduction

Noise generation and the propagation of noise from a single wind turbine are analyzed. Under certain conditions, the A-weighted sound pressure level $L_{pA}$ of wind turbine noise (WTN) is modulated with the blade passing frequency $f_m$. Figure 1 shows pulses of duration $\tau \approx 1/f_m$ and the time-varying modulation depth – $D_m$. In two studies (von Hünerbein, Piper, 2015; RenewableUK, 2013), $D_m$ is defined as the difference between the mean peak and the mean trough in the A-weighted RMS time series for any consecutive group

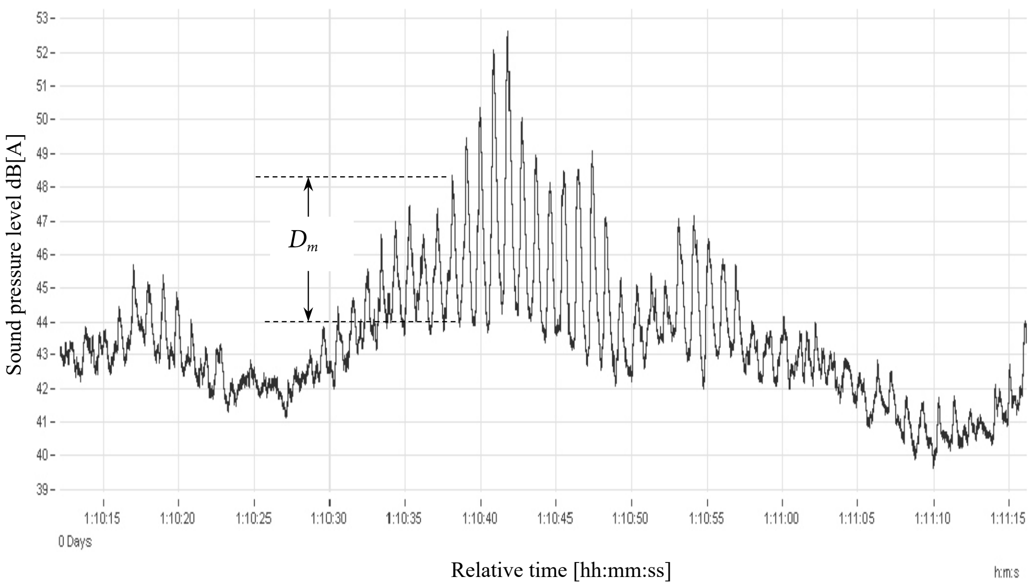


Fig. 1. Amplitude modulation of WTN recorded in a far field location (Di Napoli, 2011).

of 12 pulses that occur during the $\tau = 20$ s time interval.

Suppose every WTN segment of $\tau = 20$ s duration is characterized by the short term time-average sound level $L_{\text{Aeq},\tau}$ and modulation depth $D_m$. Recent studies prove that amplitude modulation increases WTN annoyance (Alamir *et al.*, 2021; Lotinga, 2021). Therefore, a penalty $k$ [dB] is to be added to the measured or calculated value of the short-term time-average sound level (Makarewicz, 2022):

$$\widehat{L}_{\text{Aeq},\tau} = L_{\text{Aeq},\tau} + k \text{ [dB]}. \tag{1}$$

Figure 2 shows the old penalty scheme published in (RenewableUK, 2013). For a small amplitude depth, $0 < D_m < 3$ dB, there is no penalty at all, $k = 0$. When $3 \text{ dB} < D_m < 10$ dB, the penalty$k$increases linearly from 3 dB to 6 dB. Finally, for $D_m$ exceeding 10 dB, the penalty equals 6 dB. Table 1 contains discrete values of $D_m$ and $k$. An alternative penalty scheme is proposed by Virjonen *at al.* (2019). Problem of WTN modulation was also discussed in numerous articles (Bass *et al.*, 2016; Bowdler *et al.*, 2018; Hansen *et al.*, 2018).

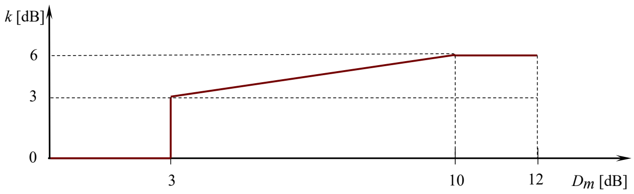


Fig. 2. The penalty scheme published in (RenewableUK, 2013).

Table 1. Discrete values of modulation depth $D_m$ and corresponding penalty $k$.

| $D_m$ [dB] | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $k$ [dB] | 0 | 0 | 0 | 3 | $3\frac{3}{7}$ | $3\frac{6}{7}$ | $4\frac{2}{7}$ | $4\frac{5}{7}$ | $5\frac{1}{7}$ | $5\frac{4}{7}$ | 6 | 6 | 6 |

## 2. Noise measurements

When $T$ denotes the time duration of WTN, $N = T/\tau$ measurements at the distance $d_*$ of the short-term A-weighted time-average sound levels $L^{(i)}_{\text{Aeq},\tau}$ and modulation depths $D^{(i)}_m$ (Fig. 3) provide complete information on WTN. It is assumed that $n \ll N$ values of $L^{(i)}_{\text{Aeq},\tau}$, $D^{(i)}_m$ yield not complete but "good enough" information. The methodology of $L_{\text{Aeq},\tau}$ and $D_m$ measurements one finds in (Hansen *et al.*, 2017; RenewableUK, 2013; IEC 61400-11, 2012). Figure 4 shows the turbine-receiver arrangement.

Figures 5 and 6 present the results of measurements with the upper and lower limits of the short-term A-weighted time-average sound levels

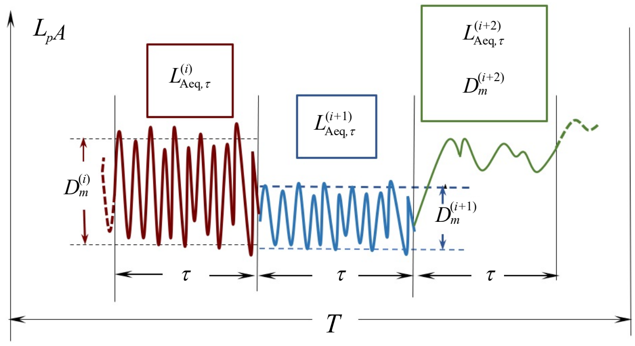


Fig. 3. Time variation of A-weighted sound level $L_{pA}$ characterized by series of pairs, $L^{(i)}_{\text{Aeq},\tau}$, $D^{(i)}_m$.

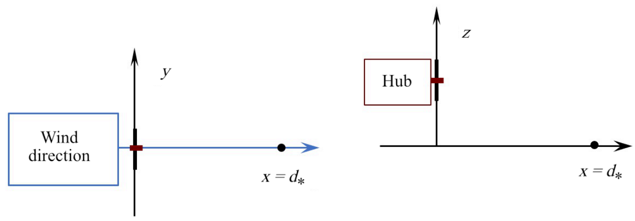


Fig. 4. Measurements of $L^{(i)}_{\text{Aeq},\tau}$ and $D^{(i)}_m$ at the reference distance $d_*$.

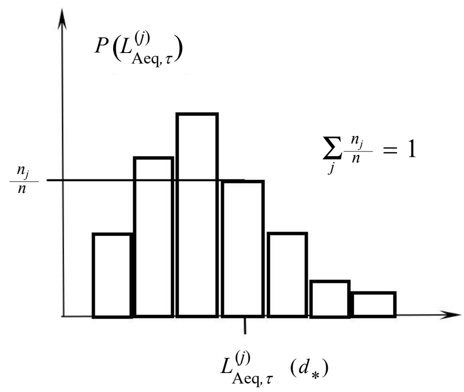


Fig. 5. Histogram of short-term A-weighted time-average sound levels at the reference distance $d_*$.

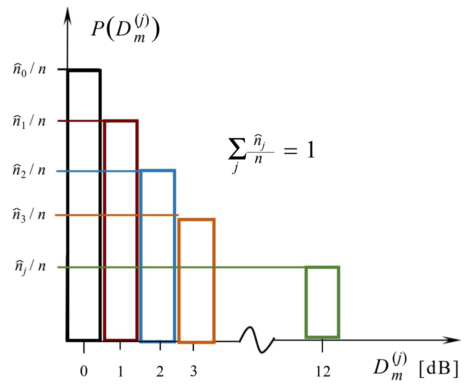


Fig. 6. Histogram of modulation depths. The probability $P = \widehat{n}_0/n$, obtained for $D_m = 0$, corresponds to non-modulated intervals $\tau$ (Fig. 3).

(e.g., $L^{(j)}_{\text{Aeq},\tau} - 2.5$ dB; $L^{(j)}_{\text{Aeq},\tau} + 2.5$ dB) and modulation depths (e.g., $D^{(j)}_m - 0.5$ dB; $D^{(j)}_m + 0.5$ dB).

## 3. Theory

The long-term A-weighted time-average sound level is defined as (American National Standards Institute [ANSI], 2020; ISO 1996-1, 2016):

$$L_{\text{Aeq},T} = 10\log\frac{\langle p_A^2\rangle_T}{p_o^2}, \qquad p_o = 20\ \mu\text{Pa}, \tag{2}$$

where (Fig. 5)

$$\frac{\langle p_A^2\rangle_T}{p_o^2} = \frac{1}{T}\int_0^T \frac{p_A^2}{p_o^2}\,\mathrm{d}t = \sum_j P\left(L_{\text{Aeq},\tau}^{(j)}\right)\cdot 10^{0.1L_{\text{Aeq},\tau}^{(j)}} \tag{3}$$

represents the long-term A-weighted time-average squared sound pressure for the interval $T \gg \tau$ (e.g., one or a few hours). The two above expressions yield $L_{\text{Aeq},T}$ at the reference distance $d_*$, where the measurements $L_{\text{Aeq},\tau}^{(i)}$ have been performed (Fig. 5). How can these results be used for $L_{\text{Aeq},T}$ prediction at any distance, $d \neq d_*$? When the distance $d$ between the turbine and the receiver exceeds the double rotor disc diameter, the turbine blades could be replaced by a point source at the hub height (Makarewicz, 2011; Ecotière, 2015). The momentary A-weighted squared sound pressure can be written as (Forssén *et al.*, 2010; Australian Standard AS 4959, 2010; Plovsing, Søndergaard, 2011):

$$\frac{p_A^2(t)}{p_o^2} = \frac{W_A(t)}{W_o}\cdot F(d), \qquad W_o = 10^{-12}\ [\text{W}], \tag{4}$$

where $W_A(t)$ and $F(d)$ represent the A-weighted sound power and propagation function, respectively. When noise measurements are carried out with a microphone on the perfectly reflecting board and noise propagation is governed by geometrical spreading and air absorption, then (IEC 61400-11, 2012):

$$F(d) = 4\cdot\frac{d_o^2}{4\pi d^2}\exp\left(-\alpha\frac{d}{d_o}\right), \qquad d_o = 1\ \text{m}. \tag{5}$$

Symbol $\alpha$ [1/m] denotes the representative air absorption coefficient for the noise spectrum, which equals $\alpha \approx 1.15\cdot 10^{-3}$ [1/m] (Swedish Environmental Protection Agency [SEPA], 2001). More complicated propagation functions $F(d,...)$ are discussed by Hansen *et al.* (2017).

For the reference distances $d_*$ and the distance $d \neq d_*$, the short-term A-weighted time average squared sound pressure takes the form (Eq. (4)):

$$\frac{\langle p_A^2\rangle_{d_*,\tau}}{p_o^2} = \frac{\langle W_A\rangle_\tau}{W_o}\cdot F(d_*), \qquad \frac{\langle p_A^2\rangle_\tau}{p_o^2} = \frac{\langle W_A\rangle_\tau}{W_o}\cdot F(d), \tag{6}$$

where $\langle W_A\rangle_\tau$ represents the short-term A-weighted time-average sound power. Consequently, Eq. (3) yields the long-term A-weighted time-average squared sound pressure at the distance $d \neq d_*$,

$$\frac{\langle p_A^2\rangle_T}{p_o^2} = \frac{F(d)}{F(d_*)}\cdot\sum_j P\left(L_{\text{Aeq},\tau}^{(j)}\right)\cdot 10^{0.1L_{\text{Aeq},\tau}^{(j)}}, \tag{7}$$

and Eqs. (2), (4), (7) combine into the long-term A-weighted time-average sound level:

$$L_{\text{Aeq},T}(d) = 10\log J_* + 10\log\frac{F(d)}{F(d_*)}, \qquad d \neq d_*. \tag{8}$$

Here (Fig. 5)

$$J_* = \sum_j P\left(L_{\text{Aeq},\tau}^{(j)}\right)\cdot 10^{0.1L_{\text{Aeq},\tau}^{(j)}(d_*)}. \tag{9}$$

For the simplest case (Eqs. (5) and (8)):

$$L_{\text{Aeq},T}(d) = 10\log J_* - 20\log\frac{d}{d_*} - 4.34\alpha\cdot(d-d_*). \tag{10}$$

Unfortunately, the value of $J_*$ (Eq. (9)) does not take into account the annoyance increase due to amplitude modulation (Alamir *et al.*, 2021; Lotinga, 2021). So, let us replace $L_{\text{Aeq},\tau}^{(j)}$ with $L_{\text{Aeq},\tau}^{(j)}+k_j$ (Eq. (1)) and write Eq. (9) again in a new form:

$$\widehat{J}_* = \sum\nolimits_j P\left(L_{\text{Aeq},\tau}^{(j)}, k_j\right)\cdot 10^{0.1\left[L_{\text{Aeq},\tau}^{(j)}+k_j\right]}. \tag{11}$$

Symbol $P(L_{\text{Aeq},\tau}^{(j)}, k_j)$ in Eq. (11) represents the unknown joint probability of co-occurrence of the short-term time-average sound level $L_{\text{Aeq},\tau}^{(j)}$ and penalty $k_j$, which depends on modulation depth $D_m^{(j)}$ (Table 1, Fig. 2). It is known that $L_{\text{Aeq},\tau}^{(j)}$ increases with wind speed (Hansen *et al.*, 2017). On the other hand, $D_j$ was found to be not related to wind speed (Paulraj, Välisuo, 2017). Accordingly, penalty $k_j$ does not depend on wind speed either. Because the joint probability of independent events is calculated as the probability of event A multiplied by the probability of event B, Eq. (11) can be written as follows:

$$\widehat{J}_* = \sum_i P\left(L_{\text{Aeq},\tau}^{(i)}\right)\cdot 10^{0.1L_{\text{Aeq},\tau}^{(i)}(d_*)}\cdot\sum_j P(k_j)\cdot 10^{0.1k_j}. \tag{12}$$

Then, in view of the identities (ANS, 2020; ISO 1996-1, 2016):

$$\sum_i P\left(L_{\text{Aeq},\tau}^{(i)}\right)\cdot 10^{0.1L_{\text{Aeq},\tau}^{(i)}} = \frac{1}{n}\sum_{i=1}^n 10^{0.1L_{\text{Aeq},\tau}^{(i)}} = 10^{0.1L_{\text{Aeq},T}}, \tag{13}$$

the combination of Eqs. (8) and (11) results in the corrected long-term A-weighted time-average sound level:

$$\widehat{L}_{\text{Aeq},T} = L_{\text{Aeq},T}(d) + \Delta\widehat{L}, \tag{14}$$

where $L_{\text{Aeq},T}(d)$ represents the calculated long-term A-weighted time-average sound level at the distance $d \neq d_*$ (Eqs. (8) and (9)), and

$$\Delta\widehat{L} = 10\log\left\{\sum_j \frac{n_j}{n}10^{0.1k_j}\right\} \tag{15}$$

represents the correction due to amplitude modulation (Fig. 6). Table 2 contains the measured values $D_m^{(j)}$, corresponding penalties $k_j$ (Table 1) and measured probabilities $P(k_j)$ (Fig. 6).

Table 2. Modulation depth $D_m^{(j)}$ with the corresponding penalty $k_j$ and probability $P(k_j)$ of its occurrence.

| $D_m^{(j)}$ [dB] | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $k_j$ | 0 | 0 | 0 | 3 | $3\frac{3}{7}$ | $3\frac{6}{7}$ | $4\frac{2}{7}$ | $4\frac{5}{7}$ | $5\frac{1}{7}$ | $5\frac{4}{7}$ | 6 | 6 | 6 |
| $P(k_j)$ | $\frac{n_o}{n}$ | $\frac{n_1}{n}$ | $\frac{n_2}{n}$ | $\frac{n_3}{n}$ | $\frac{n_4}{n}$ | $\frac{n_5}{n}$ | $\frac{n_6}{n}$ | $\frac{n_7}{n}$ | $\frac{n_8}{n}$ | $\frac{n_9}{n}$ | $\frac{n_{10}}{n}$ | $\frac{n_{11}}{n}$ | $\frac{n_{12}}{n}$ |

For example, let us determine the corrected one-hour A-weighted time-average sound level, $\widehat{L}_{\text{Aeq,1h}}$ (Eq. (13)):

$$\widehat{L}_{\text{Aeq,1h}} = L_{\text{Aeq,1h}} + \Delta\widehat{L}. \tag{16}$$

Making use of $n = 180$ values of the measured short-time A-weighted average sound level, $L_{\text{Aeq,20s}}^{(j)}$, and $n = 180$ values of the modulation depth $D_m^{(j)}$ (Table 3), Eq. (15) gives $\Delta\widehat{L} = 2.5$ dB.

Table 3. Modulation depth $D_m^{(j)}$ with the corresponding penalty $k_j$ and probability $P(k_j)$ of its occurrence for 180 values.

| $D_m^{(j)}$ [dB] | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $k_j$ | 0 | 0 | 0 | 3 | $3\frac{3}{7}$ | $3\frac{6}{7}$ | $4\frac{2}{7}$ | $4\frac{5}{7}$ | $5\frac{1}{7}$ | $5\frac{4}{7}$ | 6 |
| $P(k_j)$ | $\frac{35}{180}$ | $\frac{28}{180}$ | $\frac{25}{180}$ | $\frac{22}{180}$ | $\frac{19}{180}$ | $\frac{16}{180}$ | $\frac{13}{180}$ | $\frac{10}{180}$ | $\frac{7}{180}$ | $\frac{4}{180}$ | $\frac{1}{180}$ |

When $L_{\text{Aeq},\tau}^{(j)}(d_*)$ (Fig. 5) is measured at the distance $d_*$ with the microphone on the perfectly reflecting board, then in the simplest case of propagation (Eqs. (9) and (10)) the corrected long-term A-weighted time-average squared sound pressure at $d \neq d_*$ is determined by:

$$\widehat{L}_{\text{Aeq},T}(d) = 10\log\sum_j \frac{n_j}{n}10^{0.1L_{\text{Aeq},\tau}^{(j)}(d_*)} - 20\log\frac{d}{d_*} - 4.34\alpha\cdot(d - d_*) + \Delta\widehat{L}, \tag{17}$$

where $\alpha \approx 1.15\cdot 10^{-3}$ [1/m] (SEPA, 2001).

## 4. Conclusions

The annoyance caused by WTN increases with modulation depth (Alamir *et al.*, 2021; Lotinga, 2021). Input data of the methodology proposed here consists of the short-term time-average sound level $L_{\text{Aeq},\tau}$ (with $\tau = 20$ s) and $D_m$ (Fig. 3) measured at the reference distance $d_*$. To find the corrected long-term time-average sound level $\widehat{L}_{\text{Aeq},T}$ (with $T \gg \tau$), which takes into account annoyance increases due to modulation, one can use Eqs. (8), (9) or (14). When propagation depends mainly on geometrical spreading and air absorption, Eq. (17) is recommended. The proposed methodology needs to be tested by research.

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