Technical Note

Proposed Methodology for the Annoyance Penalty of Amplitude Modulated Wind Turbine Noise

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Amplitude modulation increases the annoyance caused by wind turbine noise. One gets the improved annoyance when a penalty is added to the measured or calculated time-average sound level. The amplitude modulated wind turbine noise consists of pulses. Each of them could be characterized by the short time-average sound level and the modulation depth. The latter determines the pulse penalty. This paper shows how to calculate the improved annoyance of amplitude modulated wind turbine noise, when the short time-average sound level and the penalty for each pulse are known. A special case of identical pulses is discussed. The proposed methodology needs to be tested by research.

Keywords: annoyance; wind turbine noise; amplitude modulation.

1. Introduction

Wind turbines have been associated with noise complaints. The problem is with suitability of the current noise limits and applied penalties. Amplitude modulation (AM) of wind turbine noise (WTN) refers to a series of noise pulses, i.e. periodic variations of the A-weighted sound pressure level, L_{pA}, with the blade passing frequency, f_m. Figure 1 shows pulses of the same duration, $\tau = 1/f_m$, and time varying modulation depth $D_m(t)$. In (Cooper, 2021; Hansen *et al.*, 2017) the methods of D_m measurements are dis-

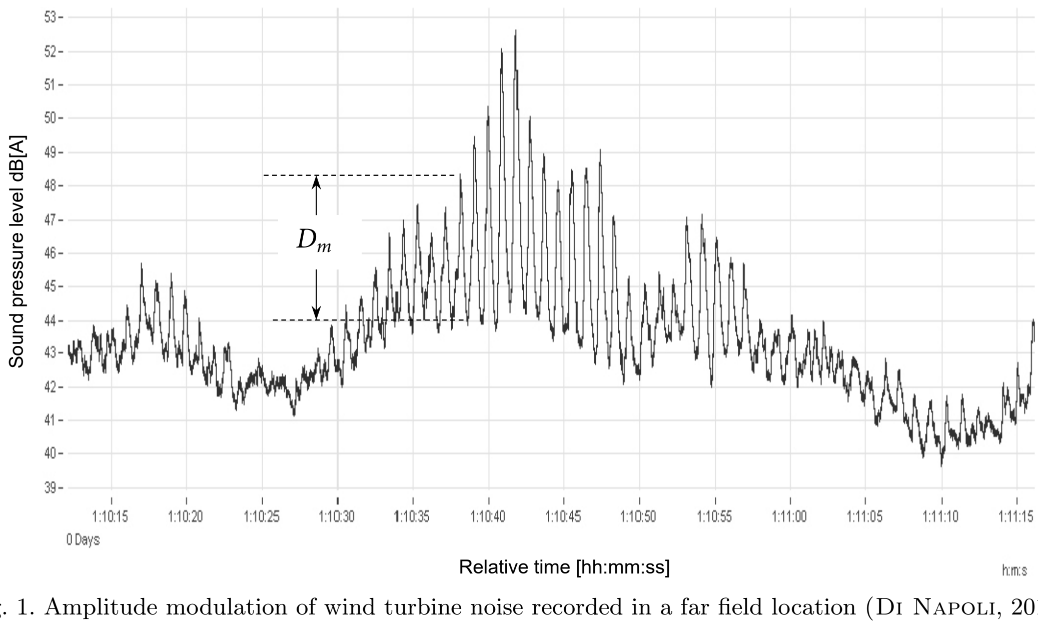

Fig. 1. Amplitude modulation of wind turbine noise recorded in a far field location (Di Napoli, 2011).

cussed. Among others, 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 of 12 pulses that occur during each 20-s block (Huenerbein, Piper, 2016; RenewableUK, 2013). The modulation frequency, $f_m \approx 1$ Hz, and the time period, $\tau \approx 1$ s, are typical for a modern wind turbine at full speed.

WTN usually is assessed in terms of the time-average sound level, $L_{\text{Aeq},T}$. It is well known that AM increases WTN annoyance (Almir *et al.*, 2021; Lotinga, 2021), so a penalty k [dB] is to be added to the measured value of $L_{\text{Aeq},T}$. In the standard (Standards New Zealand, 2010), amplitude modulation is deemed to exist if the measured A-weighted peak-to-trough levels exceed 5 dB on a regularly varying basis, or if the measured third-octave band peak-to-trough levels exceed 6 dB on a regular basis in respect of the blade pass frequency. Consequently, the penalty of $k = 5$ dB applies when amplitude modulation are present.

Figure 2 shows the penalty scheme published in (RenewableUK, 2013). The basis for this scheme are results of listening tests published in (Huenerbein *et al.*, 2012) and (Huenerbein *et al.*, 2013). When the amplitude depth is small, $0 < D_m < 3$ dB, there is no penalty, $k = 0$. For amplitude depths, 3 dB $< D_m <$ 10 dB, penalty k increases linearly from 3 dB to 6 dB. When D_m is large and exceeds 10 dB, the penalty equals 6 dB.

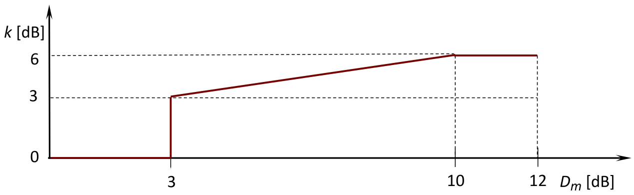

Fig. 2. The penalty scheme published in (Huenerbein *et al.*, 2012).

Table 1 presents discrete values of the modulation depth D_m and the corresponding penalties k obtained for the modulation frequency $f_m = 1$ Hz and the time period $\tau = 1$ s (Virjonene *et al.*, 2019). They characterize the annoyance caused by WTN emitted by a modern wind turbine at full speed. The continuous set of D_m and k in Fig. 3 is based on Table 1.

Table 1. Set of D_m and k.

D_m [dB]	k [dB]
2	0.9
4	3.9
8	7.9
14	9.8

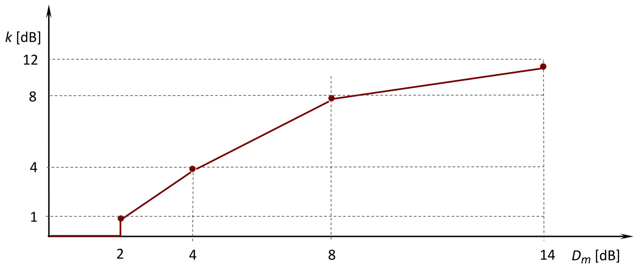

Fig. 3. Continuous values of D_m and k based on the Table 1 (Virjonen *et al.*, 2019).

Figures 2 and 3 are examples of penalty curve $k = F(D_m)$. The results reviewed in (Bass *et al.*, 2016; Bowdler *et al.*, 2018; Hansen *et al.*, 2018) discuss methods for improving both curves.

2. $L_{\text{Aeq},T}$ measurements of pulses series

In Fig. 4, a series of noise pulses is characterized by A-weighted time average sound levels, L_{Aeq,T_1}, L_{Aeq,T_2}, L_{Aeq,T_3}, L_{Aeq,T_4}, ..., and the modulation depths, D_{m_1}, D_{m_2}, D_{m_3}, D_{m_4}, ..., respectively. For the time interval (Fig. 4),

$$T = T_1 + T_2 + ..., \tag{1}$$

one gets the approximated value of the measured A-weighted time average sound level,

$$L_{\text{Aeq},T} \approx 10 \log \left\{ \frac{T_1}{T} 10^{0.1 L_{\text{Aeq},T_1}} + \frac{T_2}{T} 10^{0.1 L_{\text{Aeq},T_2}} + ... \right\}. \tag{2}$$

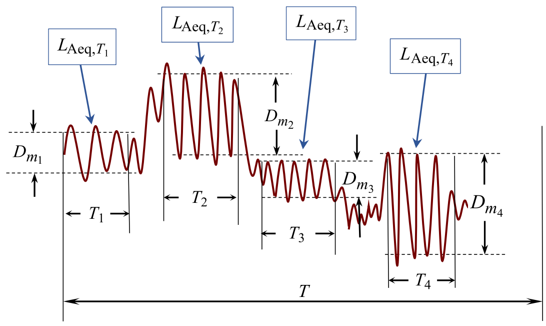

Fig. 4. Groups of noise pulses of mean modulation depths: D_{m_1}, D_{m_2}, ...

Now, with the modified A-weighted time average sound levels (Figs 2 and 3),

$$\begin{aligned} L_{\text{Aeq},T_1} &\to L_{\text{Aeq},T_1} + k_1, \\ L_{\text{Aeq},T_2} &\to L_{\text{Aeq},T_2} + k_2, ..., \end{aligned} \tag{3}$$

one arrives at the improved A-weighted time average sound level,

$$\widehat{L}_{\mathrm{Aeq},T} \approx 10\log\left\{\frac{T_1}{T}10^{0.1\left(L_{\mathrm{Aeq},T_1}+k_1\right)} + \frac{T_2}{T}10^{0.1\left(L_{\mathrm{Aeq},T_2}+k_2\right)} + \dots\right\}. \tag{4}$$

which accounts for the influence of amplitude modulation on noise annoyance.

3. $L_{\mathrm{Aeq},\tau}$ measurements of individual pulses

When modulation depth D_m varies from "pulse to pulse" (Fig. 1), the measurement of A-weighted time average sound levels, $L_{\mathrm{Aeq},\tau}$, for each pulse is needed (Fig. 5). To find both D_m and $L_{\mathrm{Aeq},\tau}$, the A-weighted squared sound pressure p_{A}^2 and the A-weighted sound pressure level are applied (ANSI, 1994; ISO, 1996),

$$L_{p\mathrm{A}} = 10\log\frac{p_A^2(t)}{p_o^2}, \qquad p_o = 20\ \mu\mathrm{Pa}. \tag{5}$$

A few hours (T) of WTN brings about annoyance that is usually measured by the time-average sound level

$$L_{\mathrm{Aeq},T} = 10\log\frac{\left\langle p_A^2\right\rangle_T}{p_o^2}. \tag{6}$$

Here

$$\frac{\left\langle p_A^2\right\rangle_T}{p_o^2} = \frac{1}{T}\int\limits_0^T 10^{0.1L_{pA}}\,\mathrm{d}t, \tag{7}$$

represents the relative value of the A-weighted time-average squared sound pressure.

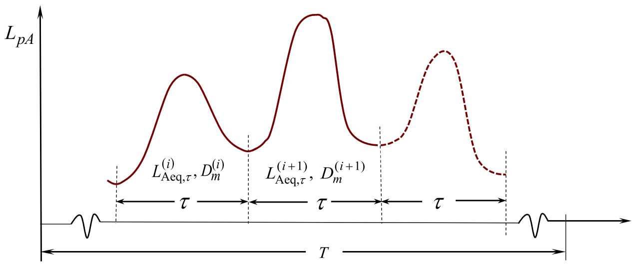

Fig. 5. A single pulse of τ duration is characterized by the short time-average sound level $L_{\mathrm{Aeq},\tau}$ and the modulation depth D_m.

When WTN is modulated $n = T/\tau$ times within the time interval T (Fig. 1), then the i-th pulse is characterized by the *short time-average sound level*,

$$L^{(i)}_{\mathrm{Aeq},\tau} = 10\log\left\{\frac{1}{\tau}\int\limits_{(i-1)\cdot\tau}^{i\cdot\tau}\frac{p_A^2}{p_o^2}\,\mathrm{d}t\right\}, \tag{8}$$

and the *modulation depth* D_{m_i}, where $i = 1, 2, \dots, n$. From Eqs (2)–(4) one gets the measured time average sound level (Eq. (2))

$$L_{\mathrm{Aeq},T} = 10\log\left\{\frac{1}{n}\sum_{i=1}^{n}10^{0.1L^{(i)}_{\mathrm{Aeq},\tau}}\right\}. \tag{9}$$

AM increases the WTN annoyance, therefore the modification of formula (9) is needed:

$$L^{(i)}_{\mathrm{Aeq},\tau} \rightarrow L^{(i)}_{\mathrm{Aeq},\tau} + k\left(D_{m_i}\right). \tag{10}$$

Figures 2 and 3 provide k values for the measured modulation depth D_{m_i}. Consequently, Eq. (9) leads to

$$\widehat{L}_{\mathrm{Aeq},T} = 10\log\left\{\frac{1}{n}\sum_{i=1}^{n}10^{0.1\left[L^{(i)}_{\mathrm{Aeq},\tau}+k\left(D_{m_i}\right)\right]}\right\}. \tag{11}$$

The right hand side concerns annoyance increase due to AM of WTN (Fig. 1).

With the known values of $L^{(i)}_{\mathrm{Aeq},\tau}$ and $k(D_{m_i})$ one calculates the means

$$\langle e\rangle = \frac{1}{n}\sum_{i=1}^{n}10^{0.1L^{(i)}_{\mathrm{Aeq},\tau}}, \qquad \langle\varepsilon\rangle = \frac{1}{n}\sum_{i=1}^{n}10^{0.1k\left(D_{m_i}\right)}, \tag{12}$$

and finds the covariance,

$$\sigma^2_{e\varepsilon} = \frac{1}{n}\sum_{i=1}^{n}\left[\langle e\rangle - 10^{0.1L^{(i)}_{\mathrm{Aeq},\tau}}\right]\cdot\left[\langle\varepsilon\rangle - 10^{0.1k\left(D_{m_i}\right)}\right]. \tag{13}$$

Ultimately, Eq. (11) takes the form,

$$\widehat{L}_{\mathrm{Aeq},T} = L_{\mathrm{Aeq},T} + 10\log\left\{\langle\varepsilon\rangle\cdot\left[1+\frac{\sigma^2_{e\varepsilon}}{\langle e\rangle\langle\varepsilon\rangle}\right]\right\}, \tag{14}$$

where $L_{\mathrm{Aeq},T}$ (Eqs (6) and (7)) represents the "penalty free" time average sound level. When the modulation depth D_m is weakly correlated with the time average sound level of a single pulse $L_{\mathrm{Aeq},\tau}$, then $\sigma^2_{e\varepsilon} \ll \langle e\rangle\langle\varepsilon\rangle$, and Eqs (12) and (14) combine into

$$\widehat{L}_{\mathrm{Aeq},T} = L_{\mathrm{Aeq},T} + 10\log\left\{\frac{1}{n}\sum_{i=1}^{n}10^{0.1k\left(D_{m_i}\right)}\right\}. \tag{15}$$

4. Conclusions

It is well known that annoyance of amplitude modulated wind turbine noise increases with modulation depth. Taking into account Figs 2 and 3, and Eq. (3), one can write

$$\hat{L}_{\mathrm{Aeq},T} = L_{\mathrm{Aeq},T} + \kappa\cdot D_m, \tag{16}$$

where $\kappa \approx 0.7$. For noise pulses – thumps which are characterized by the short time-average sound level $L^{(i)}_{\mathrm{Aeq},\tau}$ and the modulation depth D_{m_i} (Fig. 5), formulae (11) and (15) give $\widehat{L}_{\mathrm{Aeq},T}$ – the improved measure of wind turbine noise annoyance. Formulae (11), (15), and (16) have to be proven, because penalty schemes (Figs 2 and 3) have been obtained in specific circumstances. In other words, listening tests are needed to find a correlation between the calculated values $\widehat{L}_{\mathrm{Aeq},T}$ and subjective annoyance.

References

1. Alamir M.A., Hansen K.L., Catcheside P. (2021), Penalties applied to wind farm noise: current allowable limits, influencing factors, and their development, *Journal of Cleaner Production*, **295**: 126393, doi: 10.1016/j.jclepro.2021.126393.
2. ANSI S1.1-1994 (1994), *Acoustical Terminology*.
3. Bass J. *et al.* (2016), *Method for rating amplitude modulation in wind turbine noise*, Version 1, Institute of Acoustics, IOA Working Group.
4. Bowdler D.B., Cand M., Lea H., Hayes M., Irvine G. (2018), Wind turbine noise amplitude penalty considerations, *Proceedings of the Institute of Acoustics*, **40**: 253–261.
5. Cooper C. (2021), Wind farm noise – modulation of the amplitude, *Acoustics*, **3**(2): 364–390, doi: 10.3390/acoustics3020025.
6. Di Napoli C. (2011), Long distance amplitude modulation of wind turbine noise, *Fourth International Meeting on Wind Turbine Noise*, Rome, Italy.
7. Hansen C.H., Doolan C.J., Hansen K.L. (2017), *Wind Farm Noise: Measurements, Assessment and Control*, John Wiley & Sons Ltd.
8. Hansen K.L., Zajamsek B., Hansen C.H. (2018), Towards a reasonable penalty for amplitude modulated wind turbine noise, *Acoustics Australia*, **46**(1): 21–25, doi: 10.1007/s40857-018-0132-0.
9. Huenerbein S., King A., Piper B., Cand M. (2012), *Wind turbine amplitude modulation: research to improve understanding as to its cause and effect. Work Package B2. Final Report to RenewableUK*.
10. Huenerbein S., Davies B., Moorhouse A., Cand A., Piper B. (2013), Dose response relation of amplitude modulation (AM) and affective response, *RenewableUK Conference*, Birmingham.
11. Huenerbein S., Piper B. (2016), Affective response to amplitude modulated wind turbine noise, *R-th International Meeting on Wind Turbine Noise*, Glasgow.
12. ISO 1996-1 (1996), *Acoustics-Description, measurement and assessment of environmental noise*, Part 1.
13. Lotinga M.J.B. (2021), Subjective responses to wind turbine noise amplitude modulation, *9th International Conference on Wind Turbine Noise*, Remote from Europe, 2021.
14. RenewableUK (2013), *Template Planning Condition on Amplitude Modulation*.
15. Standards New Zealand (2010), NZS 6808:2010 *Acoustics – Wind farm noise in Standards New Zealand*, 2010: 1–43.
16. Virjonen P., Hongisto V., Radun R. (2019), Annoyance penalty of periodically amplitude-modulated wide-band sound, *The Journal of the Acoustical Society of America*, **146**(6): 4159–4170, doi: 10.1121/1.5133478.