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Thump noise prediction

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Summary
For some wind profiles wind turbines produce thumps. They could be described by two noise characteristics: modulation depth, ΔL_{pA}, and the time average sound level, $L_{Aeq\,\tau}$. Wind profile at heights encompassing the full rotor plane is quantified by two wind parameters: the speed mean and the wind shear coefficient. To predict the thump noise characteristics for any wind profile, one needs two turbine parameters. They can be adjusted from a single measurement of wind parameters and the concurrent measurement of noise characteristics. The theory presented here is based on two assumptions: "the bulk of sound energy is emitted from the blade tips" and "wind speed of constant direction varies with the height above the ground".

1. Introduction
Periodic changes in the A-weighted sound pressure level produced by a wind turbine, $L_{pA}(t)$, account for thump noise. Such a noise could be described by the modulation depth,

$$\Delta L_{pA} = L_{pA}^{(\max)} - L_{pA}^{(\min)}, \tag{1}$$

and the time average sound level, $L_{Aeq\,\tau}$.The engineering prediction models of L_{pA} and $L_{Aeq\,\tau}$ are based on a non-directional point source (see Refs.[1-7] and the literature cited in [8]). Making use of Di Napoli's conclusion that "the modulation depth does not decrease with the distance" [9], we write,

$$L_{pA}(t) \approx 10\log\frac{W_A(t)}{W_o} - F(\rho,h,...), \qquad L_{Aeq\,\tau} \approx 10\log\frac{\langle W_A\rangle}{W_o} - F(\rho,h,...), \tag{2}$$

where the reference sound power, $W_o = 10^{-12}[W]$, and the stated time interval τ exceeds the rotation period of a single blade: $T < \tau$. The symbols $W_A(t)$ and $\langle W_A\rangle$ denote the momentary A-weighted sound power and the time average A-weighted sound power, respectively. With ρ - horizontal distance between receiver and turbine and h - hub height, function $F(....)$ quantifies sound divergence, air attenuation,

ground effect, and other propagation phenomena. Mindful the angle $\Phi = 2\pi \cdot t / T$ (Fig.1), one gets

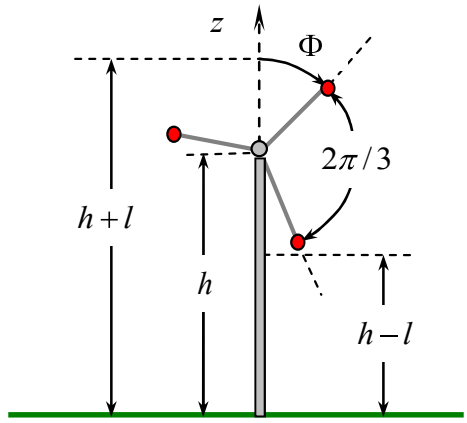

Fig.1. The wind turbine with three blades of length l and the hub at the height h.

$$\frac{\langle W_A \rangle}{W_o} = \frac{1}{T}\int_0^T \frac{W_A(t)}{W_o} dt = \frac{1}{2\pi}\int_0^{2\pi} \frac{W_A(\Phi)}{W_o} d\Phi . \tag{3}$$

For three blades the modulated noise is heard as a thump sound at the rate of blade passing frequency (Fig.2), $..... = L_{pA}(t + T/3) = L_{pA}(t) = L_{pA}(t - T/3) = ...$

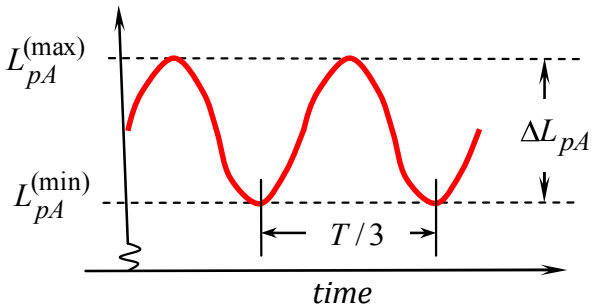

Fig.2. Thumping comes from variations in the A-weighted sound pressure level between $L_{pA}^{(\min)}$ and $L_{pA}^{(\max)}$.

Ref.[10] suggests two causes of thumps: the strict directivity of sound generated by the trailing edge of the blade and the convective amplification. The alternative explanation is based on the van den Berg effect [11-13]: the wind speed V depends on the height z (Fig.3). In this study we assume that the wind speed direction is constant (no directional shear) and the bulk of the sound energy comes from the blade tip [8,14]. The tip at the momentary height,

$$z = h + l\cos\Phi , \qquad \Phi = 2\pi \cdot t / T , \tag{4}$$

encounters the wind speed $V(z)$. Here h, l, and T denote the hub height, blade length, and rotational period of a single blade, respectively. Periodical changes in the blade tip height, z (Eq.4), are accompanied by the periodic changes in wind speed $V(z)$. The latter brings about periodic changes in the A-weighted sound power, $W_A(t)$. Finally one hears the A-weighted sound level modulation, $L_{pA}(t)$ (Fig.2), of the depth (Eqs.1,2),

$$\Delta L_{pA} = 10\log\frac{W_A^{(\max)}}{W_A^{(\min)}}\,. \tag{5}$$

The above equality says that the point source power modulation at the rate of blade passing frequency $..... = W_A(t+T/3) = W_A(t) = W_A(t-T/3) = ...$, is responsible for the thump noise (Fig.2). Now the question is how the wind parameters (speed mean and wind shear coefficient) influence the noise characteristics, $L_{Aeq\,\tau}$ (Eq.1) and ΔL_{pA} (Eq.5).

2. Wind parameters

The standard wind profile power law can be written as follows [15]:

$$V(z) = \hat{V}\cdot\left(\frac{z}{\hat{z}}\right)^{\beta}, \qquad 0 < z < \infty, \tag{6}$$

where $\hat{V}$ denotes the wind speed at the height $\hat{z}$. Urban and rural areas are characterized by the wind speed exponents, $0.15 < \beta < 0.3$ and $0.07 < \beta < 0.55$, respectively. The wind turbine generates noise in response to wind encountered by the rotor plane. Thus, to determine the sound power emitted by the blade tips (Sect.3), the wind profile $V(z)$ for the heights ($h-l < z < h+l$) is needed. Fortunately, remote sensing devices such as LIDAR or SODAR, make it possible to measure the wind speed at any height and one obtains the speeds [16,17],

$$V_1 \ldots\ldots\ldots\ldots, V_k \ldots\ldots\ldots\ldots, V_n, \tag{7}$$

with the step

$$\Delta z = \frac{2l}{n-1} \quad \text{where} \quad n \geq 2, \tag{8}$$

from $z = h-l$ to $z = h+l$. For the k-th height

$$z_k = (h-l) + 2l\frac{k-1}{n-1}, \quad \text{with} \quad k = 1,\ 2,\ \ldots\ldots, n. \tag{9}$$

the k-th wind speed equals V_k (Eq.7). For example, with $n = 2$ the above expression gives two heights , $z_1 = h-l$ and $z_2 = h+l$, for the lower and upper part of the rotor plane respectively. Now, making use of the linear approximation of the real speed profile (Eq.7),

$$V(z) = a + b\cdot z, \qquad h-l < z < h+l, \tag{10}$$

we introduce the average error of the approximation,

$$E(a,b) = \frac{1}{n}\sum_{k=1}^{n}\left[V_k - a - b\cdot z_k\right]^2, \tag{11}$$

and then estimate the unknown coefficients a and b from two equations,

$$\frac{\partial E}{\partial a} = 0 \quad \text{and} \quad \frac{\partial E}{\partial b} = 0. \tag{12}$$

Combination of Eqs.(11) and (12) yields,

$$a = \frac{\langle z^2\rangle\langle V\rangle - \langle z\rangle\langle zV\rangle}{\langle z^2\rangle - \langle z\rangle^2} \quad \text{and} \quad b = \frac{\langle zV\rangle - \langle z\rangle\langle V\rangle}{\langle z^2\rangle - \langle z\rangle^2}, \tag{13}$$

where the first and the second moment of the height z_k (Eq.9) are as follows:

$$\langle z \rangle = h\,, \qquad \langle z^2 \rangle = h^2 + \frac{n+1}{3(n-1)} l^2 . \tag{14}$$

The mean of the wind speed, $\langle V \rangle$, and the height-weighted mean wind speed, $\langle zV \rangle$, can be calculated from:

$$\langle V \rangle = \frac{1}{n}\sum_{k=1}^{n} V_k\,, \qquad \langle zV \rangle = \frac{1}{n}\sum_{k=1}^{n} z_k \cdot V_k\,. \tag{15}$$

Finally, Eqs.(7,10) bring about the formula for the wind speed,

$$V(z) = \langle V \rangle \cdot \left[1 + \varepsilon \cdot \frac{z-h}{l} \right], \qquad h-l < z < h+l\,, \tag{16}$$

with the *wind shear coefficient*,

$$\varepsilon = \frac{3(n-1)}{(n+1)l} \left[\frac{\langle zV \rangle}{\langle V \rangle} - h \right]. \tag{17}$$

Low level jet (Fig.3) brings about the negative wind shear coefficient, $\varepsilon < 0$.

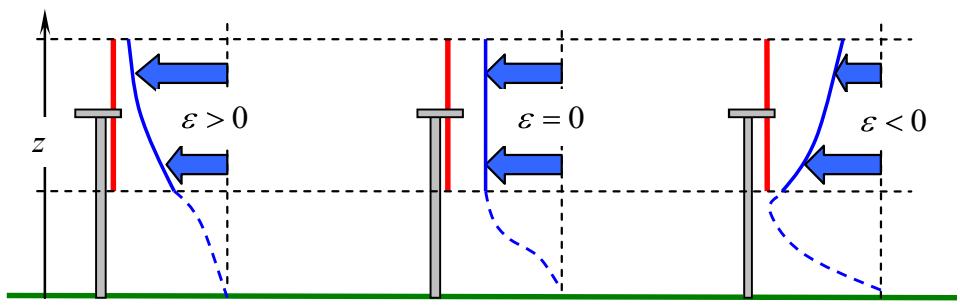

Fig.3. The wind shear coefficient ε (Eq.9) describes the wind profile at rotor plane, $h-l < z < h+l$.

For the special case of two measurements ($V_1 = V - \Delta V$, and $V_2 = V + \Delta V$), at the lower and upper tips of the rotor plane ($z_1 = h - l$ and $z_2 = h + l$), Eq.(15) leads to,

$$\langle V \rangle = V \quad \text{and} \quad \langle zV \rangle = hV + l \cdot \Delta V\,. \tag{18}$$

Finally, with $n = 2$ formula (17) simplifies to the form,

$$\varepsilon = \frac{\Delta V}{l \cdot V}\,, \tag{19}$$

and subsequently the linear approximation of the wind speed profile (Eq.16) transforms into,

$$V(z) = \langle V \rangle \cdot \left[1 + \frac{\Delta V}{V} \frac{z-h}{l} \right], \qquad h-l < z < h+l\,. \tag{20}$$

If the standard power law (with the exponent β, and the wind speed $\hat{V}$ at the height $\hat{z}$) describes wind profile, then in Eq.(16) the wind speed mean, $\langle V \rangle$, and the wind shear coefficient, ε, should be replaced by,

$$\langle V \rangle \to \hat{V} \cdot \left(\frac{h}{\hat{z}} \right)^{\beta}, \qquad \varepsilon \to \frac{\beta l}{h}\,. \tag{21}$$

3. Noise characteristics

Theory [18-21] points out that the relative A-weighted sound power from a single blade can be written as,

$$\frac{\hat{W}_A}{W_o} = A \cdot \left[\frac{V(z)}{V_o}\right]^n, \qquad V_o = 1[m/s], \tag{22}$$

where $V(z)$ denotes the wind speed (Eq.16) at the blade tip height (Eq.4). The unknown turbine parameters, A and n, characterize the wind turbine under consideration. Both need to be adjusted. At the moment t i.e. for the angle $\Phi = 2\pi \cdot t/T$ (Fig.1), the heights of all three blade tips are (Eq.4),

$$z_1 = h + l\cos\Phi, \qquad z_2 = h + l\cos(\Phi - 2\pi/3), \qquad z_3 = h + l\cos(\Phi + 2\pi/3). \tag{23}$$

Thus the A-weighted sound power from all three blades is (Eqs.16,22,23),

$$\frac{W_A(t)}{W_o} = A\left[\frac{\langle V\rangle}{V_o}\right]^n \cdot F(t). \tag{24}$$

The *modulation function* $F(t)$ consists of tree terms,

$$F(t) = g(\Phi) + g(\Phi - 2\pi/3) + g(\Phi + 2\pi/3), \tag{25}$$

where the

$$g(\Phi) = [1 + \varepsilon\cos\Phi]^n, \qquad \Phi = 2\pi \cdot t/T. \tag{26}$$

As an example, Fig.4 shows the plots of $g(\Phi)$, $g(\Phi - 2\pi/3)$, and $g(\Phi + 2\pi/3)$ (Eq.25) for the wind shear coefficient $\varepsilon = 0.5$ (Eq.17), and turbine parameter, $n = 5$.

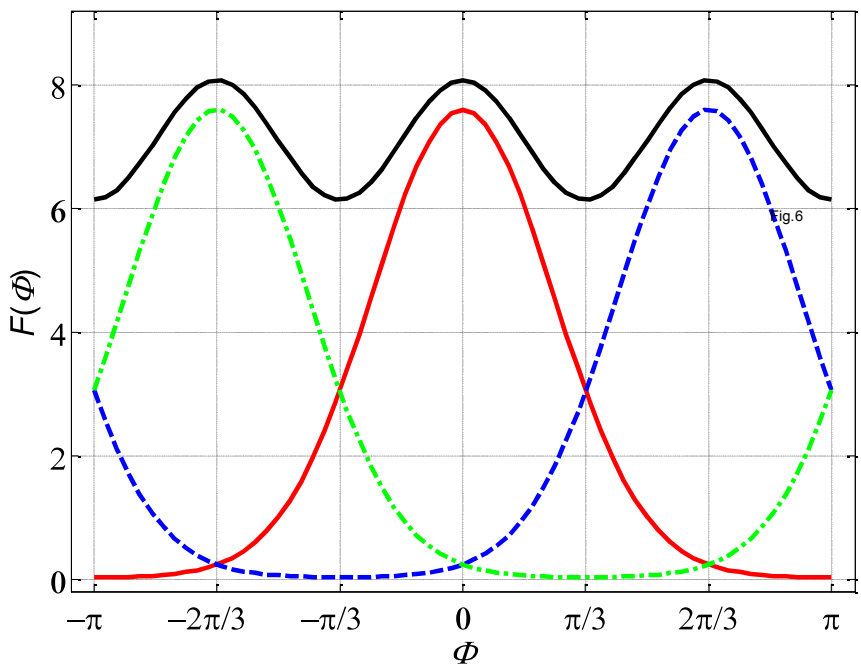

Fig.4. Three elements of the modulation function $F(\Phi)$ with $\Phi = 2\pi N \cdot t$ (Eq.25), for the wind shear coefficient $\varepsilon = 0.5$ (Eq.17) the turbine parameter $n = 4$ (Eq.24).

For any wind shear coefficient, ε, two extrema of $F(\Phi)$ (Eq.25) occur at $\Phi = 0$ and $\Phi = \pi/3$ [20,21],

$$F_1 = g(0) + g(-2\pi/3) + g(+2\pi/3), \qquad F_2 = g(\pi/3) + g(-\pi/3) + g(\pi). \tag{27}$$

For either positive or negative values of ε, the modulation depth equals (Eqs.5,24,25),

$$\Delta L_{pA} = |M| \qquad \text{with} \qquad M(n,\varepsilon) = 10\log\frac{[1+\varepsilon]^n + 2\cdot[1-\varepsilon/2]^n}{[1-\varepsilon]^n + 2\cdot[1+\varepsilon/2]^n}. \tag{28}$$

No that $M(n,-\varepsilon) = -M(n,\varepsilon)$.

To find the turbine parameters A and n (Eq.24), concurrent measurements of wind parameters, $\langle V\rangle_*; \varepsilon_*$, and noise parameters , $\Delta L^*_{pA}; L^*_{Aeq\,\tau}$, are needed.

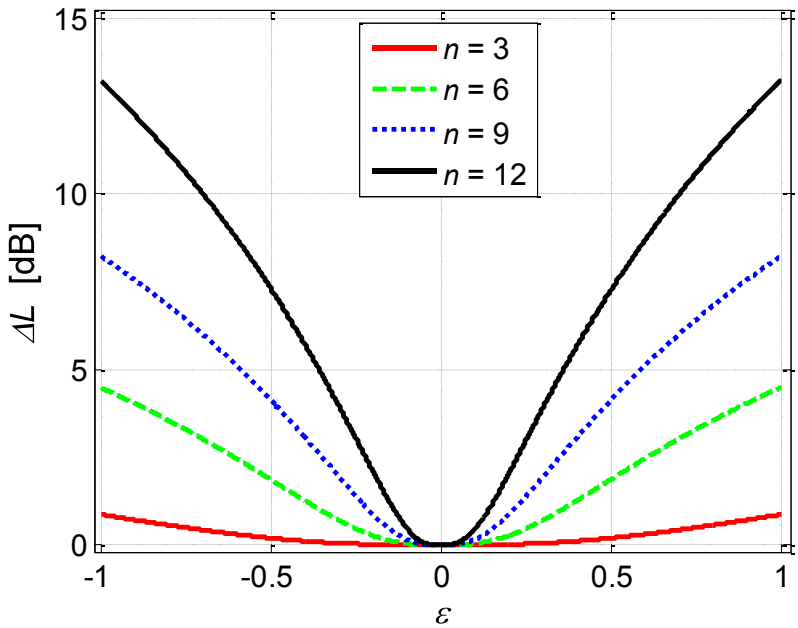

Fig.5. The thump noise characteristic, ΔL_{pA} (Eq.16), plotted for negative and positive wind shear coefficient, ε (Fig.3, Eq.17)

Example 1

Suppose that concurrent measurement of the wind shear coefficient and modulation depth yields $\varepsilon_* = 0.6$ and $\Delta L^*_{pA} = 4$ dB, respectively. Accordingly the plot in Fig.5 shows that the wind turbine under consideration is characterized by: $n = 9$. Now, for any future wind shear coefficient ε (e.g., 0.8) the plot in Fig.5 with $n = 9$ gives the corresponding modulation depth ΔL_{pA} (e.g. 12 dB), valid at any distance from the turbine (Eq.1, Ref.[9]).

To determine the time average sound level, $L_{Aeq\,\tau}$, we apply Eqs.(2,3,24-26) and arrive at the relative value of the time average A-weighted sound power ,

$$\frac{\langle W_A\rangle}{W_o} = 3A\langle g\rangle\cdot\left[\frac{\langle V\rangle}{V_o}\right]^n, \tag{29}$$

with the mean,

$$\langle g \rangle = \frac{1}{2\pi} \int_0^{2\pi} [1 + \varepsilon \cos \Phi]^n d\Phi . \tag{30}$$

Ultimately the time-average sound level becomes (Eqs.2,29),

$$L_{Aeq\,\tau} \approx 10n \log \frac{\langle V \rangle}{V_o} + 10 \log [3A \cdot \langle g \rangle] - F(d, h, ...) . \tag{31}$$

The logarithmic dependence of $L_{Aeq\,\tau}$ on the wind speed complies with many measurements (e.g. Refs.[5,22-24]). How to adjust the second wind parameter *A* ?

As was demonstrated above (Example 1), the first turbine parameter, n, can be determined from the plot in Fig.5 and the measured wind shear coefficient ε_*. The latter gives the numerical value of the mean (Eq.30),

$$\langle g \rangle_* = \frac{1}{2\pi} \int_0^{2\pi} [1 + \varepsilon_* \cos \Phi]^n d\Phi . \tag{32}$$

Then, making use of the measured time-average sound level, $L^*_{Aeq\,\tau}$, and the mean wind speed, $\langle V \rangle_*$ we rewrite Eq.(31),

$$L^*_{Aeq\,\tau} \approx 10n \log \frac{\langle V \rangle_*}{V_o} + 10 \log [3A \cdot \langle g \rangle_*] - F(d, h, ...) . \tag{33}$$

Finally, from formulae (31) and (33) it follows that:

$$L_{Aeq\,\tau} \approx 10n \log \frac{\langle V \rangle}{\langle V \rangle_*} \frac{\langle g \rangle}{\langle g \rangle_*} + L^*_{Aeq\,\tau} . \tag{34}$$

Note that the stated time interval τ exceeds the rotation period of a single blade T (Fig.2).

Example 2

Assume the mean wind speed and wind shear coefficient are, $\langle V \rangle_* = 10$ m/s and $\varepsilon_* = 0.6$. The latter wind parameter and the plot in Fig.5 yields the first turbine parameter, $n = 9$, and consequently the mean defined by Eq.(32): $\langle g \rangle_* = 14.9$. If the noise measurement at the distance d_* results in, for example, $L^*_{Aeq\,\tau} = 40$ dB, then at the same location, $d = d_*$, with the known wind parameters, $\langle V \rangle$ and ε, the time average sound level can be predicted from (Eq.34),

$$L_{Aeq\,\tau} \approx 90 \log \frac{\langle V \rangle}{10} \frac{\langle g \rangle}{14.9} + 40 \text{ dB}, \tag{35}$$

where

$$\langle g \rangle = \frac{1}{2\pi} \int_0^{2\pi} [1 + \varepsilon \cos \Phi]^9 d\Phi . \tag{36}$$

4. Influence of refraction

Unfortunately, even distant turbine noise causes annoyance, so refraction can't be ignored [9,]. Fig.6 illustrates the influence of wind induced refraction on noise propagation.

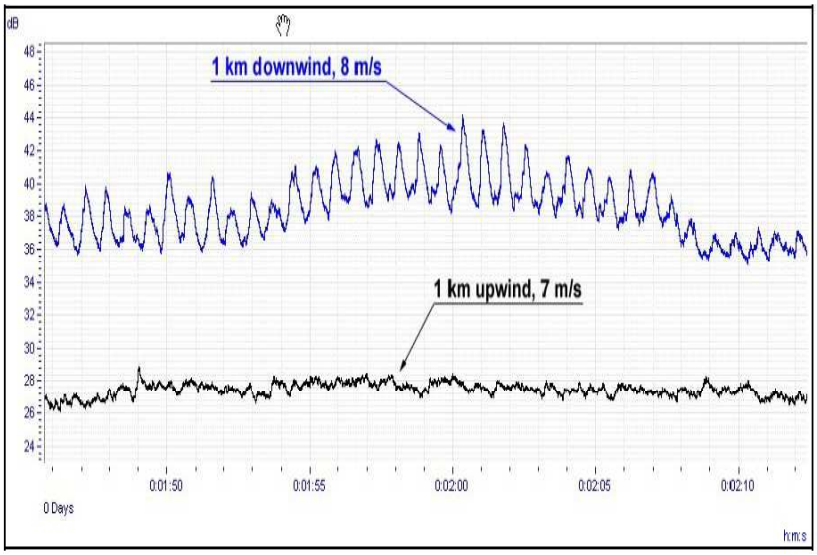

Fig.6. Thump noise for down- and upwind propagation (Ref.9).

As expected, for downwind propagation the value of $L_{Aeq\,\tau}^{(down)}$ exceeds the upwind value of $L_{Aeq\,\tau}^{(up)}$ at the same horizontal distance from the turbine. In Ref.20 it is shown, that under upwind conditions the partially ensonified zone (Fig.7) separates the fully ensonified zone (close to the turbine) and the shadow zone (far away from the turbine).

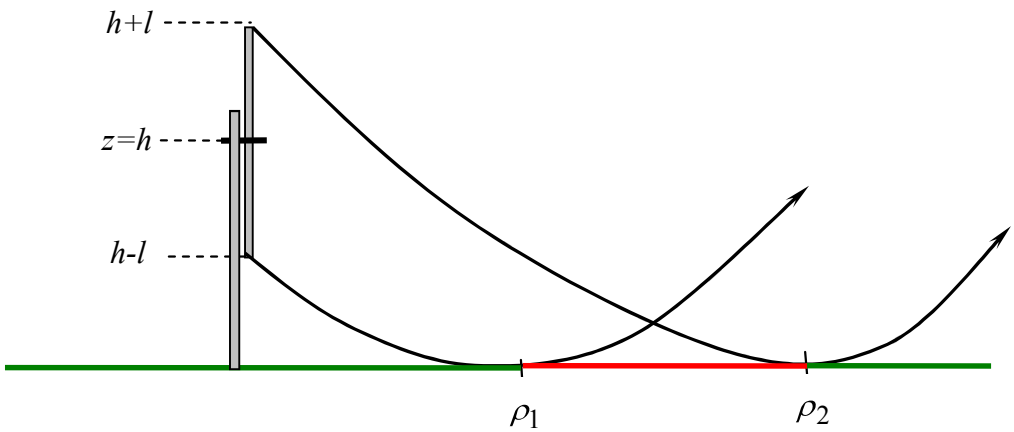

Fig.7 Partially ensonified zone, $\rho_1 < \rho < \rho_2$ (Ref.20).

In Ref.(20) refraction is described in terms of the wind speed linear profile fitted to the power law profile (Eq.6) and the rotor plane is treated as a two-dimensional circular

source in the vertical plane. Within the partially ensonified zone, the refraction effect is described by the correction $\Delta L_{WA}(\rho)$ to the A-weighted sound power level (Eq.2): $L_{WA} = 10\log[W_A / W_o]$.

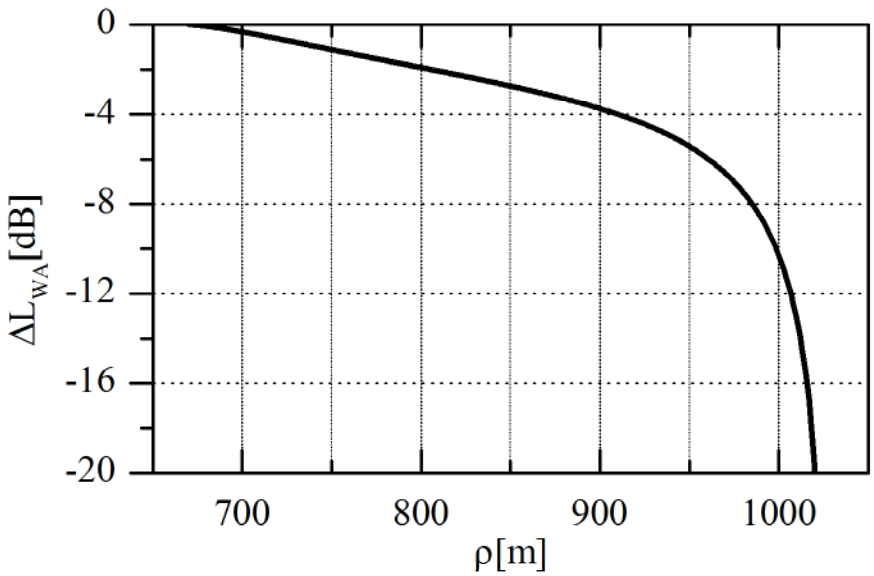

Fig.8. Refraction correction ΔL_{WA} to the A-weighted sound power level L_{WA} (Eq.2), as a function of the horizontal distance $670m < \rho < 1250m$, within the partly ensonified zone (Fig.7).

The results presented in Re.[20] would be useful in practical applications as they give a quick estimate of the effect of refraction on wind turbine noise.

5. Conclusions

In this study, the wind at heights encompassing the full rotor plane, $h - l < z < h + l$ (Fig.1), is described in terms of the mean wind speed $\langle V \rangle$ (Eq.15) and the wind shear coefficient, ε (Eq.17). To predict the characteristics of thump noise, i.e., the modulation depth ΔL_{pA} (Fig.5, Eq.28) and time-average sound level, $L_{Aeq\,\tau}$ (Eq.34) for any wind parameters, $\langle V \rangle ; \varepsilon$, one requires simultaneous measurements of noise characteristics, $\Delta L^*_{pA} ; L^*_{Aeq\,\tau}$, and wind parameters, $\langle V \rangle_* ; \varepsilon_*$ (Fig.8).

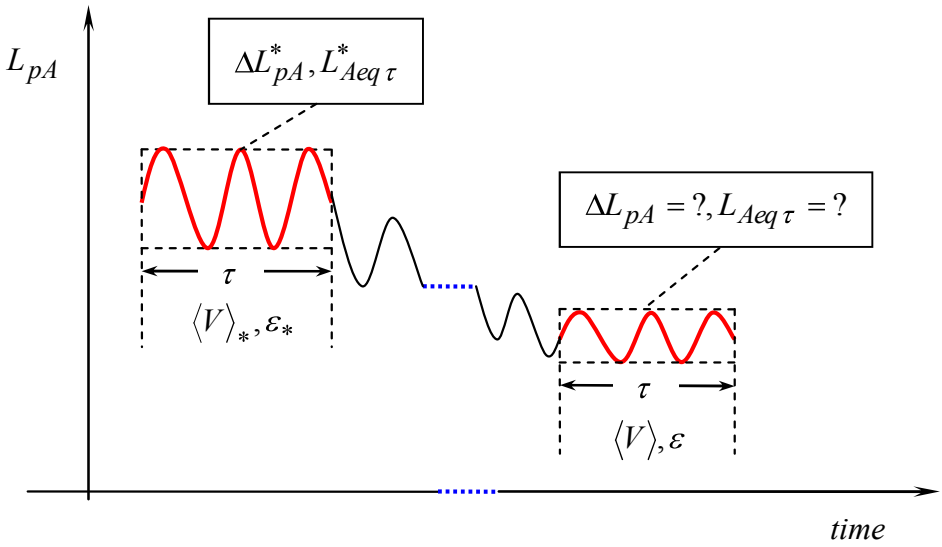

Fig.8. To predict noise characteristics, ΔL_{pA} (Fig.5, Eq.28) and $L_{Aeq\,\tau}$ (Eq.34) for a given $\langle V \rangle; \varepsilon$, one needs concurrent noise measurements, $\Delta L^*_{pA}; L^*_{Aeq\,\tau}$, and wind speed measurements, $\langle V \rangle_*; \varepsilon_*$ (Eqs.15,17).

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