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Research Article
Published: 30 Mar, 2018
SF Journal of Aviation and Aeronautical Science

Wind Turbine as a Point Source of Noise

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Abstract

Practically the sound energy of a wind turbine is produced by the blades, a few tens of meters long. Despite this the noise prediction models assume that the sound energy is emitted by a point source at the hub height. The replacement of the rotor disc – the real source by a point source brings about an error in the predicted sound level. It is shown that this error does not exceed 1dB, when the hub height, slant distance to the tower, and blade length meet certain conditions.

Keywords: Wind turbine; Noise; Blade lengths

Introduction

Wind turbine sound is a fast growing problem across the world: noise at low levels evokes annoyance not because it interferes with communication, but because it interferes with the natural quiet and the sounds of nature. It is produced by two major sources: [1] the rotor hub and moving blades. A British company recently announced it has been developing blades of up to 100 meters in length. Oerlemans at al. [2] have shown that the blade noise is produced at the outer part of the blades. Despite this the standard for measuring the sound power level from wind turbines [3], and the prediction models in common use (see e.g. Refs. [4-11]) are based on the assumption that the sound comes from a single point source located at hub height. To assess the maximal value of possible error, ΔL, in Ref. [12] we assumed a perfectly reflecting ground surface and the most unfavorable condition of noise emission, i.e. that all the sound energy is produced by the blade tips (Figure 1). In the present study the error ΔL is calculated for more realistic conditions: the ground is assumed to be soft and propagation is changed by atmospheric turbulence and downwind ground reflections.

Theory

The commonly used prediction models [4-11] neglect refraction and the A-weighted sound pressure level can be calculated from,

$$L_A = L_{WA} + 10\log\left(\frac{r_o^2}{2\pi r^2}G(r)\right) - A(r),\ r_o = 1m \qquad (1)$$

where L_{WA} is the A-weighted sound power level re.1 pW of a point source at the hub height (Figure 1) and $A(r)$ describes attenuation due to atmospheric absorption (see below).

In Refs. [13,14] one can find the function $G(r)$, which quantifies the pure ground effect, i.e., non-disturbed ground absorption and interference between the direct and reflected waves,

$$G = \left[1 + \gamma \frac{r^2}{(h_s + h_r)^2}\right]^{-1} \qquad (2)$$

Here h_s and h_r are the source- and receiver heights, $r = \sqrt{d^2 + (h_s - h_r)^2}$ is the source receiver distance, and γ denotes the adjustable ground parameter. The value of $\gamma=0$ corresponds to a perfectly reflecting ground surface. If the average height of the ray above the ground, $(h_s+h_r)/2$, grows, then the influence of ground decreases, $G\to 1$. Consequently, with $r\to\infty$ one gets $G\to 0$. The formula (2) has been verified by Attenborough et al. [14,15]. To estimate γ, one needs simultaneous measurements of the A-weighted sound level, $L_A(d)$ and $L_A(2d)$, at two locations (d, h_r), and $(2d, h_r)$ (Figure 2).

With the source and receiver close to the ground, $h_s \ll d$ and $h_r \ll d$, the ground parameter can be calculated from (Eqs. 1,2),

$$\gamma = \frac{m-1}{4-m}\cdot\left(\frac{h_s + h_r}{d}\right)^2, \qquad (3)$$

where

$$m \approx \frac{1}{4}10^{-0.0005d}\cdot 10^{0.1[L_A(d) - L_A(2d)]} \qquad (4)$$

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Received Date: *12 Feb 2018*
Accepted Date: *25 Mar 2018*
Published Date: *30 Mar 2018*

Citation: *Makarewicz R, Gołębiewski R. Wind Turbine as a Point Source of Noise. SF J Aviation Aeronaut Sci. 2018; 1(1): 1010.*

Table 1: Ground parameter γ (Esq.3,4) calculated for the slant distance and heights, $h_s + h_r = 5m$ (Figure 2).

$L_A(d)$-$L_A(2d)$	7	8	9	10	11	12
γ	$6.5\cdot10^{-4}$	$5.2\cdot10^{-4}$	$4.1\cdot10^{-3}$	$8.2\cdot10^{-3}$	$1.9\cdot10^{-2}$	$2.6\cdot10^{-2}$

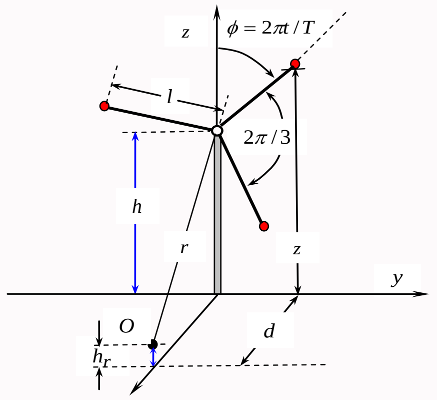

Figure 1: Blade tips as a sound sources rotating with the angular frequency ω =2π/T. The receiver O is close to the x-axis ($h_r << d$).

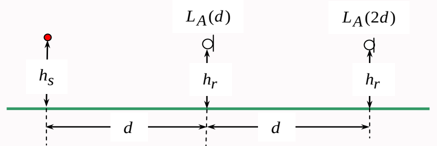

Figure 2: To estimate the ground parameter γ, simultaneous measurements of the A -weighted sound levels, $L_A(d)$ and $L_A(2d)$, are needed (Eqs.3,4).

Table 1 shows γ variations, for a few sound level differences, $L_A(d)$- $L_A(2d)$, when the source receiver distance $d=50m$, and the sum of heights equals, $h_s + h_r = 5m$ (Figure 2).

With the period of a blade rotation T[s], the time varying height of a blade tip (sound source) becomes (Figure 1),

$$z = h + l\cos\varphi,\ h > l \qquad (5)$$

where the angle of rotation for three tips is given by, $\phi = 2\pi t/T$, $2\pi\cdot(t/T+1/3)$, and $2\pi\cdot(t/T-1/3)$, respectively. When the tip height exceeds the receiver height, $h_r << h$-l, the pure ground effect (Eq.3) for a rotating tip is described as follows,

$$\hat{G} \approx \left[1+\gamma\frac{r^2(\phi)}{z^2(\phi)}\right]^{-1}, \qquad (6)$$

where z is defined by Eq.(5) and the tip-receiver distance equals (Fig.1),

$$r \approx \sqrt{d^2 + l^2\sin^2\phi + (h + l\cos\phi)^2}\ . \qquad (7)$$

If one takes into account the atmospheric turbulence which eliminate interference between direct and reflected waves, then the modified ground effect can be approximated by [15-17],

$$\tilde{G} \approx \left[1+\beta\frac{r}{z}\right]^{-1}, \qquad (8)$$

where $\beta > 0$. Comparing Eqs. (6) and (8) we see that the turbulences diminishes the ground attenuation: with $\gamma\cdot r^2 >> z$ and β - $r >> z$, one gets (Eqs.1,6,8): $\hat{G} \propto r^{-2}$ and $\tilde{G} \propto r^{-1}$, respectively. Considering geometrical divergence, r^{-2}, far away from the source one could expect a drop of 12 dB and 9 dB in the A-weighted sound pressure level, L_A, per doubling of distance, $r \to 2r$.

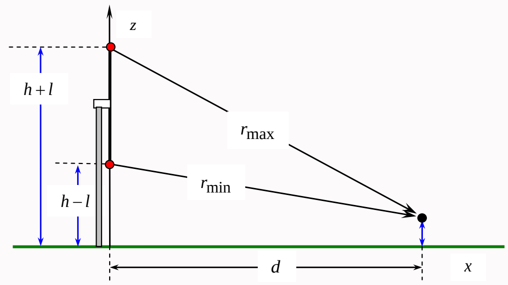

Figure 3: The longest and shortest distances from a rotating tip to the receiver, r_{max} and r_{min} (Eq.7).

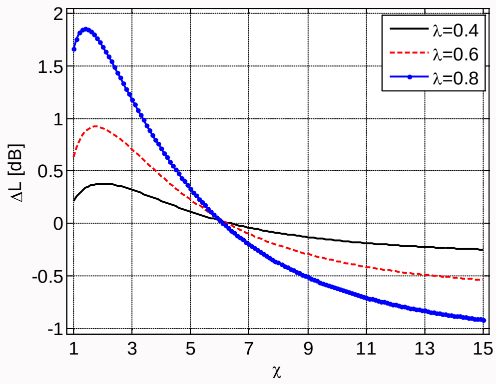

Figure 4: Dependence of the error ΔL (Eqs. 20,21) on the relative distance, $\chi = d/h$, relative blade length, $\lambda=l/h$ (Figure 1), and the ground parameter, γ =0.01 (Table 1).

In reality, far away from a wind turbine, the bouncing of the downwind rays results in a 3 dB decrease in L_A per doubling of distance [18]. This effect can be described by (Eqs. 6,8):

$$\breve{G} \approx 1 + \alpha\frac{r}{z},\ \alpha > 0 \qquad (9)$$

In Eq. (1) the value of $A(r)$ depends on the source - receiver distance r (Eq.7) and quantifies the sound attenuation caused by atmospheric absorption. In Ref. [7] one finds,

$$A = 0.005\cdot r \qquad (10)$$

For each blade tip, the difference between the longest and shorten distances r is (Fig.3),

$$\Delta r(d) = r_{max} - r_{min} = \sqrt{d^2 + (h+l)^2} - \sqrt{d^2 + (h-l)^2} \qquad (11)$$

The value of Δr decreases with the slant distance d from $\Delta r(0)=2l$ (a few tens of meters) to $\Delta r(\infty)=0$. Consequently, the air absorption of sound emitted from a rotating tip can be approximated by the constant value of (Eq.10),

$$A \approx 0.005\cdot\sqrt{d^2 + h^2}\ , \qquad (12)$$

as if the sound was emitted by the hub (Figure 1). Finally, Eqs. (1,6,8,9,12) imply the relative A-weighted squared sound pressure from a single tip,

$$\frac{p_A^2(t)}{p_o^2} = \frac{W_A}{W_o}10^{-0.0005\sqrt{d^2+h^2}}\frac{r_o^2}{2\pi r^2(t)}\cdot G\left[\frac{r(t)}{z(t)}\right] \qquad (13)$$

Here $P_0=10^{-5}$ Pa, $W_0 = 10^{-12}W$, and W_A denote the A-weighted sound power.

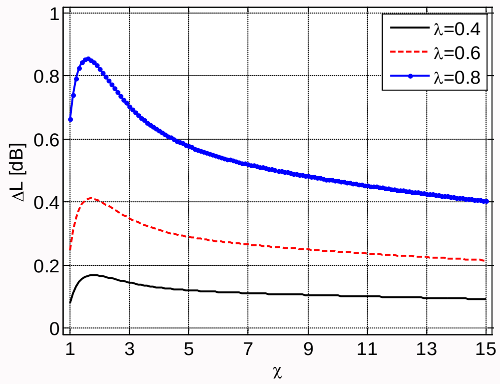

Figure 5: Dependence of the error ΔL (Eqs. 22,23) on the relative distance, $\chi = d/h$, relative blade length, $\lambda = l/h$ (Figure 1), and $\beta = 0.1$ (Eq.8) .

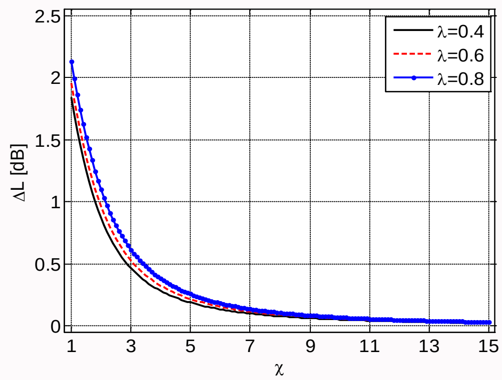

Figure 6: Dependence of the error ΔL (Eqs. 24,25) on the relative distance, $\chi = d/h$, relative blade length, $\lambda = l/h$ (Figure 1), and α=0.01 (Eq.9).

Note that the blade rotation yields the time varying tip height $z(t)$ (Eq.5) and the time varying tip-receiver distance, $r(t)$ (Eq.7).

Error of Point Source Assumption

The time average value of the squared A-weighted sound pressure from 3 tips equals (Eq.13),

$$\frac{\langle p_A^2 \rangle_{tips}}{p_o^2} = \frac{1}{2\pi}\frac{3W_A}{W_o}10^{-0.0005\sqrt{d^2+h^2}} \cdot J(l) \tag{14}$$

where

$$J(l) = \frac{1}{T}\int_0^T \frac{r_o^2}{r^2(t)} G\left[\frac{r(t)}{z(t)}\right] dt = \frac{1}{2\pi}\int_0^{2\pi} \frac{r_o^2}{r^2(\phi)} G\left[\frac{r(\phi)}{z(\phi)}\right] d\phi \tag{15}$$

The explicit form of $G[r/z]$ and $r(\phi)/z(\phi)$ are given by Eqs.(6,8,9), and Esq.(5,7).

If 3 blades collapse into a hub ($l \to 0$, Figure 1) and a point source arises, then the above integral transforms into,

$$J(0) = \frac{r_o^2}{d^2+h^2} G\left[\frac{\sqrt{d^2+h^2}}{h}\right] \tag{16}$$

The above formula represents the point source model [4-11]. Its combination with Eq. (14) leads to the noise characteristic of a three blade wind turbine,

$$\frac{\langle p_A^2 \rangle_{hub}}{p_o^2} = \frac{1}{2\pi}\frac{3W_A}{W_o}10^{-0.0005\sqrt{d^2+h^2}} \cdot J(0) \tag{17}$$

However replacement of the rotor disc of diameter $2l$ (Figure 1) by a point source brings about an error that equals (Eqs. 14,17),

$$\Delta L = 10\log\frac{\langle p_A^2 \rangle_{tips}}{\langle p_A^2 \rangle_{hub}} = 10\log\frac{J(l)}{J(0)} \tag{18}$$

To determine the above error we introduce the relative height of the tip above the ground, $Z = z(\phi)/h$, and the relative tip-receiver distance, $R = r(\phi)/h$ (Eqs. 5,7),

$$Z(\varphi,\lambda) = 1 + \lambda\cos\varphi,\; R(\varphi,\chi,\lambda) = \sqrt{1+\chi^2+\lambda^2+2\lambda\cos\varphi} \tag{19}$$

where $\chi = d/h$ and $\lambda = l/h$.

In the case of pure ground effect, without turbulence and the bouncing downwind rays, Eqs. (6,15,16,18) combine into,

$$\Delta L = 10\log\hat{F}(\chi,\lambda,\gamma), \tag{20}$$

where (Eq.19)

$$\hat{F} = (1+\chi^2)\left[1+\gamma\cdot(1+\chi^2)\right]\cdot\frac{1}{2\pi}\int_0^{2\pi}\frac{Z^2(\phi,\lambda)d\phi}{R^2(\phi,\chi,\lambda)\cdot\left[Z^2(\phi,\lambda)+\gamma\cdot R^2(\phi,\chi,\lambda)\right]} \tag{21}$$

The results of the calculations are plotted in Fig. 4.

The influence of turbulence on ground effect is illustrated by the plots in Figure 5, which have been obtained from Eqs. (8,15,16) and (18)

$$\Delta L = 10\log\tilde{F}(\chi,\lambda,\gamma), \tag{22}$$

where

$$\tilde{F} = (1+\chi^2)\left[1+\beta\cdot\sqrt{1+\chi^2}\right]\cdot\frac{1}{2\pi}\int_0^{2\pi}\frac{Z(\phi,\lambda)d\phi}{R^2(\phi,\chi,\lambda)\cdot\left[Z(\phi,\lambda)+\beta\cdot R(\phi,\chi,\lambda)\right]} \tag{23}$$

Finally, the case of the bouncing downwind rays is characterized by (Eqs. 9,15,16,18),

$$\Delta L = 10\log\breve{F}(\chi,\lambda,\gamma), \tag{24}$$

with

$$\breve{F} = \frac{1+\chi^2}{1+\alpha\cdot\sqrt{1+\chi^2}}\cdot\frac{1}{2\pi}\int_0^{2\pi}\frac{\left[1+\alpha\cdot R(\phi,\chi,\lambda)\right]d\phi}{1+R^2(\phi,\chi,\lambda)}, \tag{25}$$

and illustrated in Figure 6.

Conclusions

The plots in Figures (4), (5), and (6) make clear that the error ΔL (Eq.18) is less than

1 dB,

- under any conditions of propagation (pure ground effect, or influenced either by turbulence or downwind bouncing),
- for real blades, $l < 0.8h$,
- at any realistic slant distance, $d > 2h$.

In other words, the point source model can be applied. It appears that the presented above mathematical approach presented above does not need experimental verification.

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