J. Wind Eng. Ind. Aerodyn. 132 (2014) 49–53

Contents lists available at ScienceDirect

Journal of Wind Engineering and Industrial Aerodynamics

journal homepage: www.elsevier.com/locate/jweia

The partially ensonified zone of wind turbine noise

Rufin Makarewicz*, Roman Gołębiewski

Institute of Acoustics, Faculty of Physics, A. Mickiewicz University, Umultowska 85, 61-614 Poznan, Poland

ARTICLE INFO

Article history:
Received 10 February 2014
Received in revised form
25 June 2014
Accepted 25 June 2014
Available online 16 July 2014

Keywords:
Wind turbine noise
Refraction
Shadow zone

ABSTRACT

Complaints concerning wind turbine noise have been more widespread in recent years. This is a modeling paper on noise generated by a three blade wind turbine. A single blade is treated as a linear source with the sound power growing from the hub to the tip. The main contribution of this study is the idea of the partially ensonified zone (PEZ), which separates the fully ensonified zone (close to the turbine) and the shadow zone (far away from the turbine). PEZ comes from a blade – a linear source and the wind shear refraction. The commonly used methods provide the A-weighted time average, L_{AeqT}, inside the fully ensonified zone. The main finding is the method of L_{AeqT} estimation within PEZ.

1. Introduction

This is a modeling paper on the propagation of noise from a three blade wind turbine (Fig. 1A).

In many countries this noise is assessed in terms of the A-weighted time average sound level, L_{AeqT}. The engineering models of L_{AeqT} prediction are based on point source sound divergence over a flat ground surface and air absorption (e.g. EGS, 1994; Forssen et al., 2010; Plovsing and Sondergaard 2011; TRS, 1998; VROM, 1999).

$$L_{AeqT} \approx L_{WA} - 10\log\left[2\pi\left(\frac{\rho}{l_o}\right)^2\right] - 0.005\cdot\frac{\rho}{l_o}, \quad l_o = 1\text{ m}. \tag{1}$$

In this study (Section 3), the refraction correction to the A-weighted sound power, ΔL_{WA}, will be introduced. The rotor disc can be treated as a point source (Fig. 1), when the distance ρ exceeds the rotor diameter $2l$ (Makarewicz, 2011). The wind speed dependence on the altitude, $V(z)$, causes refraction and ultimately the shadow zone (Fig. 1B). According to the ray theory, the shadow zone is a region where no sound can be heard. As a matter of fact, the silence is not absolute because of scattering and diffraction. With polar coordinates, the boundary between the shadow zone and fully ensonified zone (Fig. 2) is determined by the angle from the line of wind direction, α, and the distance from the tower, ρ (Attenborough, 2007; Makarewicz, 1989)

$$\rho(\alpha) = \mu\frac{h}{\sqrt{\cos\alpha}}. \tag{2}$$

The parameter μ is discussed in Section 3.

Anyway, if the wind turbine is modeled by a point source (Fig. 1), then L_{AeqT} variations along the straight line (at the angle α – Fig. 2) look similar to those in Fig. 3A at the distance $\rho(\alpha)$, where the shadow zone begins, there is a sudden fall in L_{AeqT}. However, in practice this is not true. The plot in Fig. 3B is more feasible: L_{AeqT} declines smoothly between ρ_1 and ρ_2. In such a case, the inequalities, $2l < \rho < \rho_1$ and $\rho > \rho_2$, determine the borders of the fully ensonified zone and the shadow zone, respectively. They are separated by the partially ensonified zone (Makarewicz 2013).

Within the fully ensonified zone $\rho < \rho_1$ (dashed $x$axis on Fig. 4B), all points of the rotor disc participate in noise emission at the receiver. Only the points of the upper part of the rotor disc, $\hat{z} < z < h + l$ (Fig. 4A), participate in the sound reaching the partially ensonified zone, $\rho_1 < \rho < \rho_2$ (solid x axis – Fig. 4B).

Instead of the point source at the hub (Fig. 1), in this study we used a two dimensional rotor disc as a sound source. This results in the partially ensonified zone, $\rho_1 < \rho < \rho_2$.

(Figs. 3 and 4), finally modifies Eq.(1) (see Section 3).

2. Noise generation

Several models of blade sound generation have been proposed (Hayashi et al., 2012; Hubbard and Shepherd, 2004; Lee et al., 2013; Leloudas et al., 2007; Moriarty and Migliore, 2003; Oerlemans and Shepers, 2009; Tian et al., 2013; Wagner et al., 2003). The model presented here requires a field measurement of the A-weighted sound power, L_{WA} (IEC, 2011), in the fully ensonified zone (Fig. 4). To derive the final relationships, we consider the blade element of unit length, $l_o = 1$ m, which is located at the distance, $0 < \varsigma \le l$, from the hub (Fig. 5).

* Corresponding author.
E-mail address: makaaku@amu.edu.pl (R. Makarewicz).

http://dx.doi.org/10.1016/j.jweia.2014.06.018
0167-6105/

Due to inequality, $|V(z)-V(h)| \ll V(h)$, we neglect the wind speed differences along the rotor disc of diameter $2l$. Thus, for the altitude range, $h-l<z<h+l$, we assume the same wind speed, $V(z) \approx V(h)$. With the rotation speed, $N[rps]$, the speed of the blade element of unit length ($l_o = 1$ m) equals, $v(\varsigma) = 2\pi N\varsigma$ (Fig. 5), and the inflow speed becomes

$$U(\varsigma) \approx \sqrt{v^2(\varsigma)+V(h)^2}. \tag{3}$$

The blade tip speed, $v(l) = 2\pi Nl$, is much greater than the wind speed at the hub height,

$$V(h) \ll v(l). \tag{4}$$

The A-weighted power of sound emitted from the blade element of unit length, $l_o = 1$ m, increases not only with the inflow speed, $U(\varsigma)$ (Eq. (3)), but also with the angle of attack for the blade element at the distance, $0<\varsigma\le l$ (Fig. 6)

$$\gamma(\varsigma) \approx \arctan\frac{V(h)}{2\pi N\varsigma} - \theta(\varsigma) \tag{5}$$

where $\theta(\varsigma)$ denotes the pitch angle. A wind turbine operates most

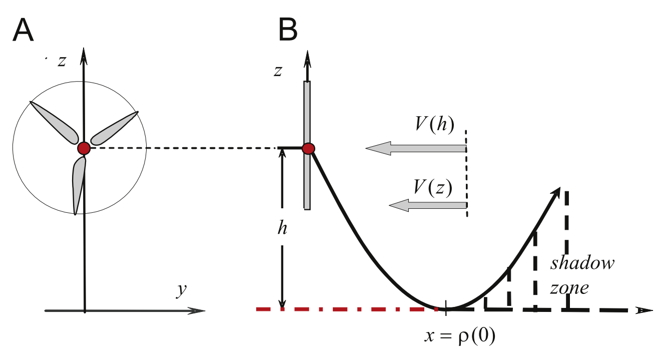

Fig. 1. Wind shear refraction with the wind speed, $V(z)$, and point source at the height h.

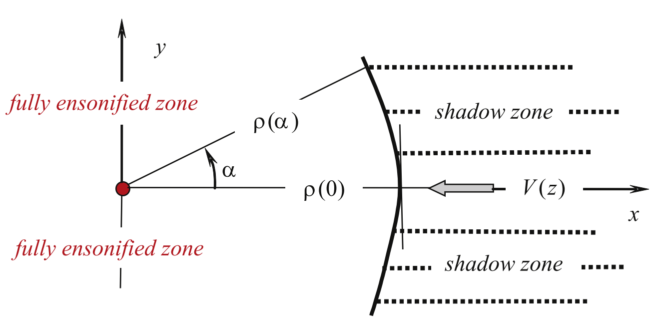

Fig. 2. The boundary between the shadow- and fully ensonified zones, $\rho(\alpha)$ (Eq.(2)). The wind blows along the x-axis with the speed $V(z)$ dependent on the height.

efficiently when the angle of attack is constant along the blade from the hub to the tip, i.e. when γ is independent of the distance, $0<\varsigma\le l$ (Fig. 5). To secure the fixed value of $\gamma=\gamma_o$ along the blade, the pitch of the blade element has to twist with the distance ς (Eq.(5)):

$$\theta(\varsigma) = \arctan\frac{V(h)}{2\pi N\varsigma} - \gamma_o \tag{6}$$

Consequently, θ decreases from $\theta(0) = \pi/2-\gamma_o$ to $\theta(l) = \arctan[V(h)/2\pi Nl]-\gamma_o$.

The energy of the sound from the blade element of unit length, $l_o = 1m$, increases with the inflow speed U and the attack angle,

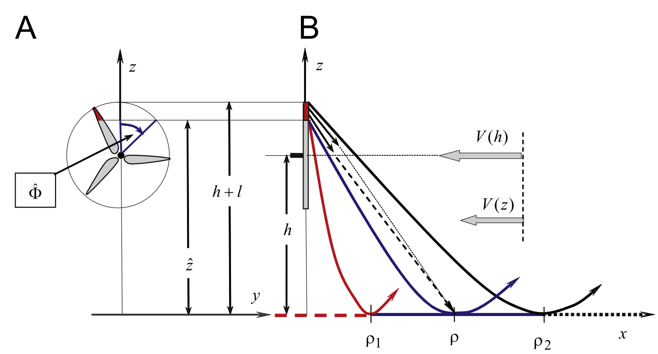

Fig. 4. Only the upper part of the rotor disc, $\hat{z}<z<h+l$, participates in the sound reaching the partially ensonified zone, $\rho_1<\rho<\rho_2$ (solid part of the x axis). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

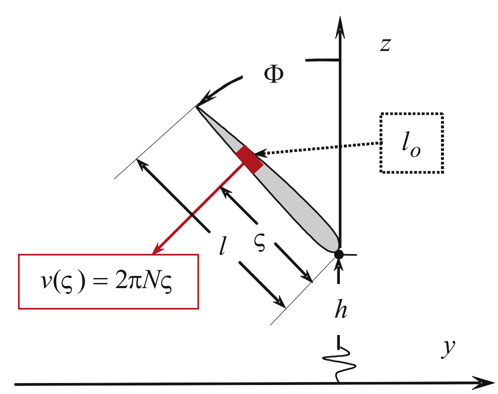

Fig. 5. The blade element of unit length, $l_o = 1$ m, at the distance ς from the hub and at the height, $z = h+\varsigma \cos \Phi$, above the ground. With the rotation speed $N[rps]$and the rotation period,$\tau[s]$, the azimuth angle equals, $\Phi = 2\pi t/\tau$, and the element speed is, $v(\varsigma) = 2\pi N\varsigma$.

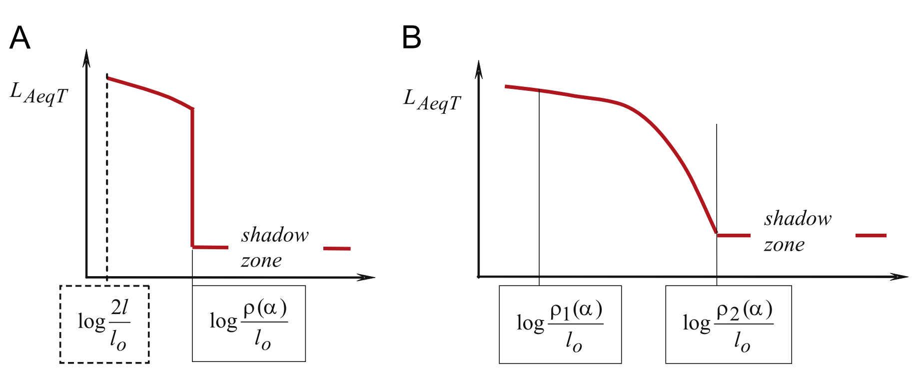

Fig. 3. The point source model gives unrealistic fall in L_{AeqT} at the distance $\rho(\alpha)$ (Eq.(2)), where the shadow zone begins (A). When the whole rotor disc is treated as a two dimensional source, the value of L_{AeqT} decreases smoothly (B).