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Cylindrical spreading of noise from a wind turbine

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ABSTRACT

Noise prediction is very important for new wind farms located near to noise sensitive receivers. To minimize uncertainties of noise level calculation, the effect of cylindrical spreading must be taken into account far away from a turbine. Cylindrical spreading of sound from point source (wine turbine) results from downwind refraction, induced by low level jet. An LLJ is characterized by a wind speed maximum of at least 10–20 m/s with peak speeds up to 30 m/s, at a height a few hundred meters above the ground. Two categories of LLJ are discussed: concaved upward and concaved downward. Cylindrical spreading begins at the critical distance, R, where the superposition of the direct and once reflected rays occurs. The method for calculation of R, for two LLJ categories, is discussed.

1. Introduction

A large increase in wind power is mandated all over the world. However, wind turbine noise appears to be a rather disturbing sound, so prediction regarding this noise is very important for new wind farms located near to noise sensitive receivers. Under-prediction leads to turbines being shut down. Conversely, the over-prediction results in available land for wind energy production being under-utilized. To minimize uncertainties in noise prediction, the upwind refraction cannot be ignored (Makarewicz and Golebiewski, 2014). In this study, the effect of cylindrical spreading, induced by downwind refraction, is discussed. This effect confirms noise measurements far away from a turbine (Willshire and Zorumski, 1987; Spera, 1994; Johansson, 2003; Sondergaard and Plovsing, 2005; Boue, 2007; Dickinson, 2010; James, 2012; Mylonas, 2014; Hansen et al., 2015). Cylindrical spreading can be explained in terms of ground reflected rays, which are modified by downwind refraction (Fig. 1, Section 2). On the other hand, downwind refraction is caused by a low level jet – LLJ (Section 2), characterized by a wind speed maximum of at least 10–20 m/s with peak speeds of up to 30 m/s, at a height a few hundred meters above the ground.

Near the turbine, air absorption and refraction only slightly distort spherical spreading (Brekhovskikh and Lysanov, 1990; Pierce, 1991; Ostashev, 1997; Salomons, 2001; Attenborough et al., 2007).Thus the sound level decreases almost 6 dB per doubling of the distance. The superposition of ground reflected rays begins at the *critical distance*, $x = R$ (Fig. 2), where both, the direct ray and once reflected ray hit the receiver on the ground (left-hand boundary of *transition zone* on Fig. 2). Because the number of superposing rays increases with horizontal distance, (Brekhovskikh and Lysanov, 1990; Salomons, 2001) further away from the turbine, $x = R + \Delta R$, the superposition of three rays occurs: the direct-, once reflected -, and two times reflected. Inside the transition zone (Fig. 2), the ray superposition nullifies the effects of air absorption and diminishes the sound level decrease per doubling of the distance significantly: instead of 6 dB one gets 5 and 4 dB. Far away from turbine, where cylindrical spreading is completed, $x >> R$ (Fig. 2), the sound level decrease per doubling distance tends to 3 dB. In Section 2 two categories of LLJ wind profile are discussed: concaved up- and downward (Figs. 6 and 10). The present study shows, how the critical distance, R, depends on the LLJ characteristics: the jet parameter, γ (Eqs. 8,19), and LLJ maximal speed, $V(H)$, with its height, H (Figs. 6 and 10). The calculated value R is not exact, because the sound speed and wind velocity profiles are idealized. For example, we neglect the sound speed gradient, the wind turning from the Coriolis force, and the dependence of R on the horizontal ray direction relative to the wind direction. This neglect simplifies the calculation procedure and will introduce some error of R estimation (Section V).

2. Downwind refraction

The elevation angle of the ray, $\alpha(z)$ (Fig. 3), quantifies the ray direction given by, $dz/dx = \tan\alpha(z)$. In order to find by integration the range of the ray, x, one needs $ctg\alpha(z)$, as an explicit function of the altitude, z.

Let $V(z)$ and $c(z)$ denote the horizontal wind speed and the adiabatic sound speed in a stratified atmosphere, respectively. Usually, the strong density stratification of LLJ results in the sound

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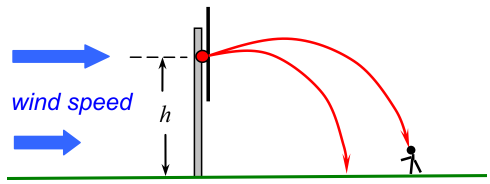

Fig. 1. Downwind refracted rays close to wind turbine.

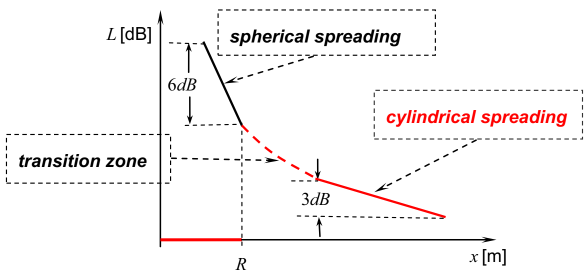

Fig. 2. The transition zone separates the zone of spherical spreading. ($x < R$) and zone of cylindrical spreading ($x > > R$).

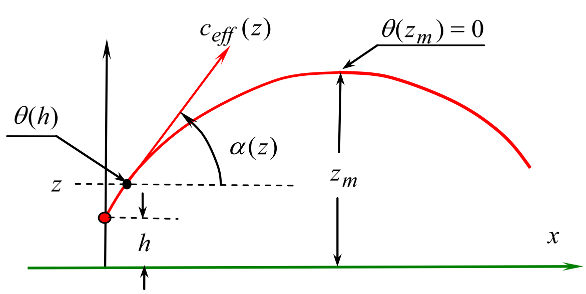

Fig. 3. At the height z direction of the ray determines the angle $\alpha(z)$ (Eq. 2, Fig. 4).

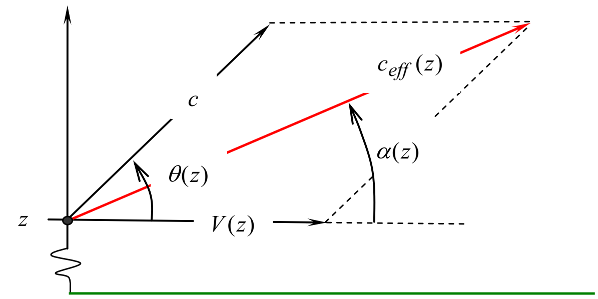

Fig. 4. The effective sound speed, $c_{eff}(z) \approx \bar{c} + V(z) \cdot \cos\alpha(z)$, depends on the mean sound speed, $\bar{c}$, and the wind speed, $V(z)$.

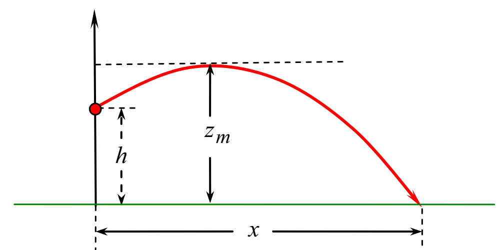

Fig. 5. The range of the direct ray, x (Eq. 6), with the height of the turning point, z_m.

speed gradient, $|dc/dz| > 0$. Thus, for the LLJ core at the height, $H = 200 - 300$ m, we will apply the mean sound speed,

$$\bar{c} = \frac{c(0) + c(H)}{2}, \tag{1}$$

where $c(0)$ and $c(H)$ denote the adiabatic sound speed at the ground, $z = 0$, and at the altitude, $z = H$, respectively. In this study it is assumed that the wind speed gradient, dV/dz prevails over the sound speed gradient, $dV/dz > > |dc/dz|$. So, the effective sound speed (Wilson, 2014) can be approximated by (Fig. 4), $c_{eff}(z) \approx \bar{c} + V(z) \cdot \cos\alpha(z)$, where $0 < z < H$.

In a moving atmosphere, the normal to the wave front, $\theta(z)$, does not usually coincide with the ray direction $\alpha(z)$. Burton's equation provides the relationship between $\alpha(z)$, $\theta(z)$, and $\bar{c}$ (Barton (1901) and formula 3.54 in Ostashev (1997)):

$$ctg\alpha(z) = \frac{\bar{c} \cdot \cos\theta(z) + V(z)}{\bar{c} \cdot \sin\theta(z)}. \tag{2}$$

On the other hand, the well-known Snell's law relates the directions of the normal to the wave front, $\theta(z)$, at the height, $h < z < z_m$, and the normal, $\theta(z_m)$, at the turning point $z = z_m$ (Fig. 3),

$$\frac{\cos\theta(z)}{\bar{c} + V(z) \cdot \cos\theta(z)} = \frac{\cos\theta(z_m)}{\bar{c} + V(z_m) \cdot \cos\theta(z_m)}. \tag{3}$$

However, at the turning point, $z = z_m$ (Fig. 3), the normal is parallel to the ground surface, $\theta(z_m) = 0$, and the above expression takes the form,

$$\cos\theta(z) = [1 + M(z_m) - M(z)]^{-1}. \tag{4}$$

Due to the small Mach number, $M(z) = V(z)/c(0) < < 1$, Eqs. (2) and (4) combine into approximation,

$$ctg\alpha(z) \approx \frac{1}{\sqrt{2[M(z_m) - M(z)]}}. \tag{5}$$

Ultimately, the sum,

$$x = \int_h^{z_m} ctg\alpha(z)dz + \int_0^{z_m} ctg\alpha(z)dz, \tag{6}$$

gives the range of the direct wave, which comes from the elevated source, $z = h$, and reaches the source on the ground, $z = 0$ (Fig. 5).

2.1. Low level jet concaved upward

Low level jet-LLJ (Fig. 6) is characterized by the jet parameter, γ (Eq. 8), wind speed maximum, $V(H)$ (at least 10–20 m/s with peak speeds up to 30 m/s), a few hundred meters above the ground, $z = H$. LLJ is formed, among others things, by diurnal changes in the thermal stratification of the surface layer over oceans, seas and deserts (Kaellstrand, 1998; Baas et al., 2009; Ranjha et al., 2013; Emeis, 2014). When the wind speed measurements, $V(H)$ and $V(h)$, and the corresponding heights, $H; h$, give inequality,

$$A = \frac{h}{H} \cdot \frac{V(H)}{V(h)} < 1, \tag{7}$$

the wind profile concaves upward (solid line in Fig. 6) and it could be described by,

$$V(z) = V(h) \cdot \frac{1 - \exp(-\gamma z)}{1 - \exp(-\gamma h)}, 0 < z < H, \tag{8}$$

where γ denotes the *jet parameter*. In order to find γ, we introduce the variable,

$\chi = \exp(-\gamma h)$, and the relative height of the wind speed maximum, $K = H/h$,

$$\frac{1 - \chi^K}{1 - \chi} = \frac{V(H)}{V(h)}. \tag{9}$$

First one determines χ, and then arrives at the jet parameter, $\gamma = -\ln\chi/h$. The height of the turbine tower, h (Fig. 1), is assumed to be known. For the very special case of $A = 1$ (Eq. 7), the wind