DOI: 10.61782/fa.2023.0616

WIND TURBINE NOISE AURALIZATION INCLUDING TONAL AND BROADBAND AEROACOUSTIC SOURCES

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ABSTRACT

The annoyance reported by people living in the vicinity of wind farms may be due to the nature of the noise, which includes significant low frequency components with a modulated temporal structure. To better understand this annoyance, it is desirable to develop a wind turbine noise auralization technique in order to perform psychoacoustic tests in a controlled manner. The physics-based synthesis tool presented here includes both tonal and broadband aeroacoustic sources. On the one hand, the tonal components at the harmonics of the blade passing frequencies are mostly due to the blade-tower interaction. On the other hand, the broadband components corresponding to trailing edge noise and turbulent inflow noise are obtained from Amiet's theory. In order to include long-range propagation effects in the synthesized sounds, parabolic equation calculations are performed for various source heights along the rotor height. This study emphasizes the influence of some key parameters on the wind turbine sounds, such as propagation range and direction, wind shear, turbulence dissipation rate and ground impedance.

Keywords: *physics-based sound synthesis, parabolic equation, amplitude modulation, shadow zone*

1. INTRODUCTION

The annoyance reported by people living in the vicinity of wind farms may be due to the nature of the noise, which includes significant low frequency components with a modulated temporal structure [1–3]. To better understand this annoyance, it is desirable to develop a physics-based wind turbine noise auralization tool technique in order to perform psychoacoustic tests in a controlled manner. Compared to the sampled-based approach, the main advantages of the physics-based approach are to control the physical parameters that drive wind turbine sounds, and to clearly separate wind turbine noise from background noise. This auralization tool must include the main broadband aeroacoustic sources, that dominate the wind turbine noise spectrum above approximately 100 Hz. Also, other tonal noise sources coming from the blade-tower interaction [4] or from gearbox vibrations may be disturbing in some circumstances.

The synthesis of wind turbine noise has lately been of increasing interest [5–8]. In this paper, we present a physics-based wind turbine noise model that allow us to synthesize noise from a 2.3 MW wind turbine over a flat ground, while including the refraction effect due to the wind speed gradient, ground reflection and scattering due to turbulence.

2. PHYSICS-BASED SYNTHESIS OF WIND TURBINE NOISE

The synthesis tool for wind turbine noise is based on an extended source model [9], in order to correctly account for ground interference effects, and to predict the right distance to the shadow zone in upwind conditions. In this model, we divide each wind turbine blade into M segments, as shown in Figure 1, and calculate the sound pressure level $L_p(f,\beta)$ of each segment at frequency f and an-

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gular position β using the point source approximation [9]:

$$L_p(f,\beta) = L_W(f,\beta) - 10\log_{10}(4\pi R(\beta)^2) + \Delta L(f,\beta) - \alpha(f)R(\beta), \tag{1}$$

where $L_W(f,\beta)$ is the sound power level, $\Delta L(f,\beta)$ is the sound pressure level relative to free field, $\alpha(f)$ is the absorption coefficient in dB/m and $R(\beta)$ is the source-receiver distance.

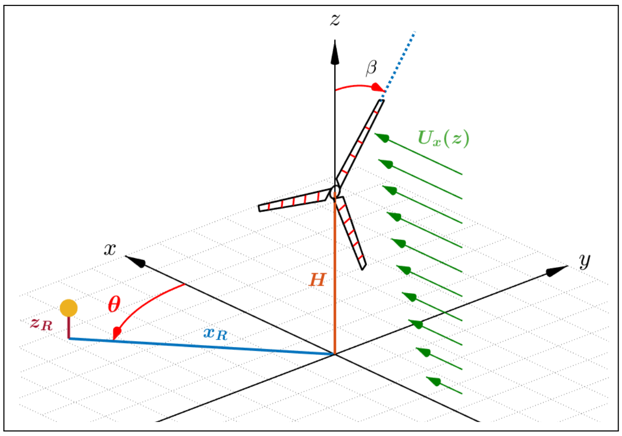

Figure 1. Schematics for the wind turbine modeling with the receiver at an angle θ with respect to the incoming wind, at a distance x_R from the base of the wind turbine and at a height z_R above the ground.

The sound power level $L_W(f,\beta)$ is calculated using Amiet's theory for trailing edge noise and turbulence interaction noise, including the rotation effects. The model is detailed in Ref. [10], with some recent modifications given in Ref. [8]. The main input parameters for the trailing edge noise model are the boundary layer parameters that are calculated with Xfoil at 99% of the chord. The main input parameter for the turbulence interaction noise model is the turbulence dissipation rate ϵ.

The refraction and ground reflection effects are calculated using a wide-angle parabolic equation model valid in moving media [11]. Using this model, wind speed gradients can be directly included without using the effective sound speed approximation, although this approximation has been shown to produce small phase errors in the context of wind turbine noise [12]. The ground impedance is estimated using the Miki model for a rigidly-backed layer. The two model parameters are the effective flow resistivity σ and the effective thickness e. To consider the effect of scattering due to turbulence, the Harmonoise engineering model is considered [8, 13].

To synthesize a time signal from the frequency-domain wind turbine noise model, we follow the method described in Mascarenhas *et al.* [6]. The method consists of firstly synthesizing the contribution of each blade segment at every angular position by converting the frequency domain response between the frequencies f_{min} and f_{max} into a time signal with the help of the Inverse Discrete Fourier transform. The individual time signals of the segments at each angular position β called grains are then arranged on the basis of their corresponding propagation time. For a smooth transition between two grains an adaptive window function is used, conserving the size of each grain while also maintaining the power of the respective grains [6].

3. TEST CASES

In this section we present some results for a 2.3 MW wind turbine of hub height of H = 80 m and diameter 93 m, as in Ref. [10]. The rotational speed Ω = 1.47 rad/s with a wind speed at hub height $U(H) = 8$ m/s, and a power law profile is considered for the wind speed $U(z)$:

$$U(z) = U(H)\left(\frac{z}{H}\right)^m, \tag{2}$$

where the wind shear coefficient m is chosen equal to 0.2 (near-neutral atmospheric conditions). The parameters of the Miki model are chosen as $\sigma = 354$ kNs/m^4 and $e = 0.0157$ m, which corresponds to the grass ground measured in summer in Ref. [14]. The turbulence dissipation rate ϵ is equal to 0.0115 m^2/s^2, which corresponds to a moderate turbulence level [15].

In the moving monopole model, one rotation is divided into N_β = 36 discrete angular blade positions as this value of N_β provides a good quality of sound synthesis [6]. We synthesize the signals of the wind turbine noise at the sampling frequency of f_s=44.1kHz between the frequencies 100 Hz and 5000 Hz for two complete rotations of the blades for various test cases described in Table 1. All four cases correspond to upwind conditions ($\theta = 180°$), for a receiver height z_R=2 m and for various ranges x_R between 500 m and 1000 m.

To compare these different cases, the spectra of the sound pressure level averaged over one rotation are plotted in Figure 2 . The differences between cases A and B are mostly due to the ground effect, with interferences that are visible between 100 and 400 Hz, and to atmospheric

Table 1. Parameters for the tests cases A to D with a propagation angle $\theta = 180°$.

Case	x_R (m)	Propagation effects
A	500	no (free-field)
B	500	yes
C	800	yes
D	1000	yes

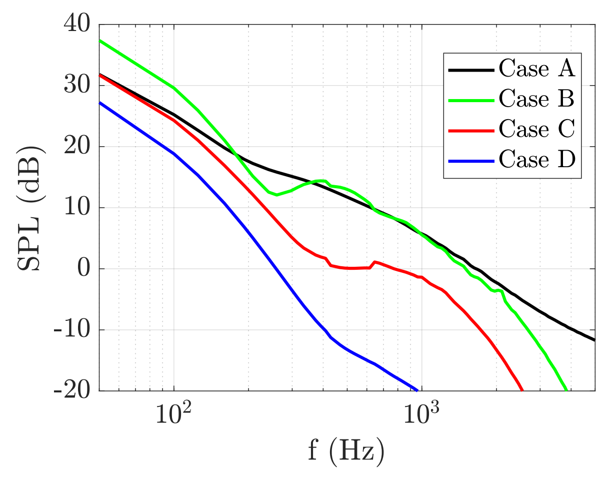

Figure 2. Narrowband spectra of time-averaged sound pressure level calculated for the test cases described in Table 1.

absorption, that reduces the spectral levels above 2 kHz. For cases C and D at higher ranges, the spectral levels are significantly lower due to the shadow zone effect.

The amplitude modulation (AM) due to the rotation of the blades is the maximum difference in $L_p(f, \beta)$ during one rotation calculated as:

$$\mathrm{AM}(f) = \max_{\beta}[L_p(f,\beta)] - \min_{\beta}[L_p(f,\beta)]. \tag{3}$$

The spectra of AM for the four cases are plotted in Figure 3. For case A in free field, AM is very small over the entire frequency band as expected for wind turbine noise aeroacoustic sources [10, 16]. For case B, an increase of AM is visible between 100 Hz and 400 Hz, that is due to the ground effect variations during the rotation of the blade, and above 600 Hz, because the receiver is in the shadow zone when the blade tip passes at the lowest heights. For case C at a distance of 800 m, the AM reaches high values because the observer moves from inside to outside the shadow during the blade rotation for all frequencies above 500 Hz. For case D at a distance of 1000 m, this only happens below 500 Hz, as the observer is always in the shadow zone for higher frequencies.

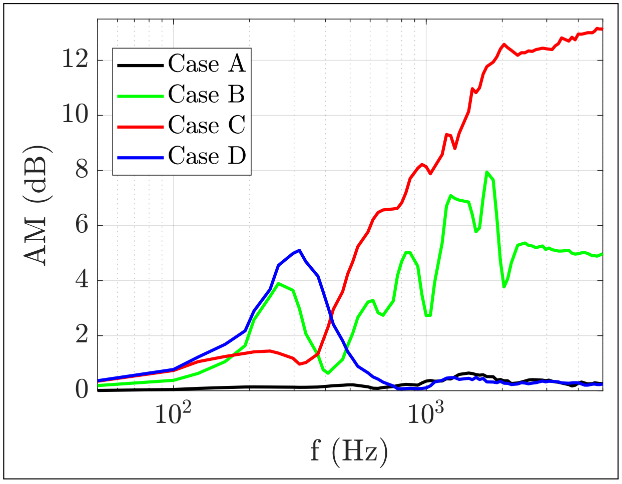

Figure 3. Narrowband spectra of the amplitude modulation in decibels calculated for the test cases described in Table 1.

4. CONCLUSION

In this paper, we have presented a physics-based auralization tool for wind turbine noise that includes broadband aeroacoustic sources and atmospheric propagation effects. We are currently in the process of adding tonal aeroacoustic sources associated to blade-tower interaction in the model. In the future, this model could be used to perform perceptive tests in controlled conditions.

5. ACKNOWLEDGMENTS

This project has received funding from the European Union's Horizon 2020 research and innovation program under the Marie Sklodowska-Curie grant agreement No 812719, and from the French National Agency for Research within the convention ANR-19-CE36-0009.

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