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## Auralization of Wind Turbine Noise Using Physics-Based Emission and Propagation Models

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### ABSTRACT

The problem of noise annoyance that is due to the characteristics of wind turbine noise such as amplitude modulation is an important factor against the building of wind farms. It would thus be beneficial to predict the noise that is generated by the wind turbines in the design phase itself. The auralization tool discussed in this article synthesizes the noise generated by wind turbine blades with the help of trailing edge noise and turbulent inflow noise models. The parabolic equation is used to include propagation effects associated to the ground impedance and the temperature and wind speed gradients. The effect of scattering due to atmospheric turbulence in the acoustic signal is added to this synthesis tool. To achieve a convincing signal of the environment of the wind turbine, pre-recorded background noise can be added to the time signals. The resulting signal corresponds to a wind turbine noise in an outdoor environment which can be used readily. The influence of the various parameters on the perception and annoyance due to wind turbine noise can be studied in detail using this tool.

Keywords: Auralization, wind turbine noise, Annoyance, Parabolic equation, Harmonoise model

### 1 INTRODUCTION

Wind energy is among a few green energy sources which serves as a replacement for conventional polluting energy sources and evidently a steady rise in the number of wind farms can be seen [3]. However one of the main issue due to the installation of wind turbines is the potential impact of the noise generated by the moving blades leading to potential causes of annoyance and disturbances in sleep patterns for people living in the vicinity of wind farms [17, 9]. One way to avert this bargain between concerns on the generated noise and the necessity for building wind farms is to predict the noise generated by the wind turbines in the design phase and accordingly adapt them to the requirements. For an accurate prediction of the noise based on controllable parameters, it is necessary for the model to be physics-based. Synthesis of this noise into time signals can also be used to study psychoacoustic questions such as disturbance and annoyance caused by wind turbine noise.

The main sources of broadband wind turbine noise as known in the literature are turbulent inflow noise (TIN), trailing edge noise (TEN) and stall noise [22, 15, 1], among which stall noise is the most intense and is produced only when the angle of attack of the blade is large. Thus, as a simplest case scenario the TIN and TEN which are observed as dominant sources of wind turbine noise are considered here. Another important component that influences the received noise is the propagation of the generated sound through an inhomogeneous atmosphere and its reflection off the semi-porous ground. In an outdoor environment, the sound received from a point source can be modelled based on the characteristics of the noise source that is modified by the influence of the propagation effects of the environment. To account for the propagation effects through the atmosphere the parabolic equation (PE) methods have been used widely [2, 6, 23] and have also been applied to the models of wind turbine noise [4, 10, 11, 5]. The new formulation of the parabolic equation as given by Ostashev *et al.* [16] is used to compute the effect of the refraction and ground reflection of the sound in a

moving medium. The effect of scattering due to turbulence in the atmosphere that is accounted for through the Harmonoise model [19] which we implement here. In this study we synthesize noise from a Megawatts wind turbine which includes the propagation effects while benefiting from the moving monopole model [5] coupled with the synthesis tool for wind turbine noise [13]. We first describe briefly the wind turbine noise model in Section 2 and present a few test cases in Section 3.

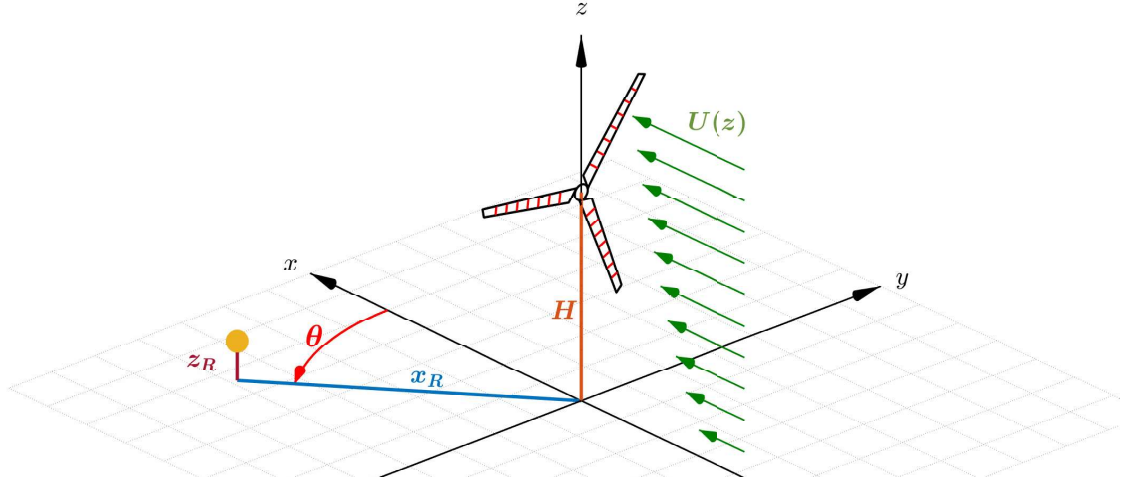


Figure 1. Schematics for the wind turbine sound synthesis tool with the receiver represented as a sphere.

## 2 WIND TURBINE NOISE SYNTHESIS MODEL

The sound pressure level ( $SPL$ ) in dB observed by a receiver from a point source in the far-field is given by [20]:

$$SPL = SPL_{ff} + \Delta L - \alpha_{abs}R, \quad (1)$$

where  $SPL_{ff}$  (dB) is the sound pressure level observed at the receiver position in free-field,  $\Delta L$  (dB) is the sound pressure level relative to free field,  $\alpha_{abs}$  (dB/m) is the atmospheric absorption coefficient [20] and  $R$  (m) is the direct distance between the point source and the receiver. The  $SPL_{ff}$  is characteristic of the source while  $(\Delta L - \alpha_{abs}R)$  includes the effects observed due to propagation of the sound through the atmosphere. For the wind turbine system, the noise from the blades can be modelled as multiple point sources along the length of the blade, whose individual sound propagates through the atmosphere [22, 5]. In the wind turbine noise model, the blades are divided into a number of segments whose contribution to the total sound is accounted for separately (Fig. 1) for the receiver at the position defined by the distance from the hub  $x_R$ , the height of the receiver  $z_R$  and the orientation of the receiver with respect to the wind direction  $\theta$ .

The wind turbine noise source model developed by Tian and Cotté [22] predicts the trailing edge noise (TEN) and turbulent inflow noise (TIN) generated by a segmented wind turbine blade based on Amiet's theory. The presented wind turbine noise model adapts this approach and predicts the  $SPL_{ff}$  (dB) for the TIN and TEN for a receiver in free field for each segment at each discrete angular positions. The TEN is computed using Goody's model of the wall pressure spectrum (WPS) [7] for the pressure side and Rozenberg and Lee's model of the WPS [12, 18] for the suction side of the airfoil. The TIN is computed using the Kolmogorov energy spectrum which is determined based on the turbulent dissipation rate (TDR)  $\epsilon(m^2/s^3)$ . The frequency-domain model approximates the complete rotation of the blade as a series of translations with discrete angular positions. Following Sinayoko *et al.* [21], the convective amplification and Doppler effect observed on account of the moving blades is considered to obtain the instantaneous PSD.

A few of the propagation effects that have an influence on the sound in the outdoor environment involve refraction due to the wind speed profile, ground reflection, atmospheric absorption, scattering due to turbulence

in the atmosphere [20]. We implement the wide angle parabolic equation in a moving medium (WAPE-MM) to account for the effect of the sound refraction and ground reflection obtaining the term  $\Delta L_{PE}$  [16]. The influence of the ground impedance parameters in the form of the normalized admittance for the boundary conditions of the WAPE-MM is important in the interference patterns caused by the wave reflected off the specific ground. These ground impedance parameters can be estimated for a real ground using the method suggested by Guillaume *et al.* [8] for the Miki model [14] which relate to the impedance observed in terms of the air flow resistivity of the ground  $\sigma(kNs/m^4)$  and the effective thickness  $e(m)$ . The estimated impedance parameters for a few realistic grounds are included in this model. For the effect of scattering due to turbulence, the Harmonoise model [19] is implemented to obtain the term  $\Delta L_{scat}$ . For consistency with the source model, the turbulence energy spectrum used is the Kolmogorov spectrum. The total relative sound pressure observed by the receiver is thus given by:

$$\Delta L = 10 \log_{10}(10^{\Delta L_{PE}/10} + 10^{\Delta L_{scat}/10}), \quad (2)$$

which accounts for the refraction due to the wind speed profile, ground reflection and the scattering due to the atmospheric turbulence.

For this study, the WAPE-MM implemented is calculated using a grid resolution of  $\Delta x = \Delta z < \lambda/20$ , where  $\lambda$  is the wavelength of the propagated sound. A second-order Salomons initial starter at  $x_S = 0$  is used at the required source height  $z_S$ . The wind speed profile moving in the positive x-direction implemented follows the power-law profile given by:

$$U_x(z) = U_{ref} \left( \frac{z}{z_{ref}} \right)^\alpha \quad (3)$$

where  $U_{ref}$  is the reference wind speed taken at the hub height  $z_{ref}=80m$  and  $\alpha$  is the wind shear exponent. The effective wind speed profile observed for a receiver at the orientation  $\theta$  is thus:  $U = U_x \cos(\theta)$ .

For the calculation of the  $\Delta L$ , the source and the receiver positions are evidently important parameters in the influence of the propagation effect. However, to be coupled with the emission model described above, the computation of the propagation effect for each segment of the blade at each height is expensive and time consuming. We benefit from the moving monopole model which suggests the computation of  $\Delta L$  for a finite number of heights and approximates the height of each the noise source of the wind turbine model to the nearest-neighboring height [5]. Following the suggestion that the approximation of 7 heights or more in the moving monopole model provides satisfactory results for the implementation of the propagation effects, we compute  $\Delta L$  for 7 heights distributed between the highest and lowest heights of the blade noise sources.

With the  $SPL_{ff}$  computed for the source model and  $\Delta L - \alpha_{abs}R$  to account for the propagation effects, we obtain the frequency response for each moving segment at each discrete angular position. To synthesize a time signal from the frequency-domain of the wind turbine noise, we use the method of Mascarenhas *et al.* [13] by synthesizing the contribution of each blade segment at every angular position by availing of the Inverse Discrete Fourier transform. The individual time-signals of the segments at each angular position termed as grains are multiplied with an adaptive window and arranged on the basis of their corresponding propagation time. The adaptive window is used with an overlap of  $\Psi=100\%$  to account for the different propagation times of each segment which is suggested [13]. As each of the blade segments in rotation are assumed to be uncorrelated with individual contribution to the total noise, the grains are synthesized separately for the TEN and TIN and then summed together at the corresponding time step. The synthesis of the total wind turbine noise is done with the inclusion of the propagation effects for a few test cases that are described in the next section.

### 3 TEST CASES

The modelled wind turbine has a hub height of  $H = 80$  m with a blade span of 45 m divided into 8 segments and rotational speed  $\Omega = 1.47$  rad/s for the blade moving with  $N_\beta = 36$  discrete angular blade positions. The receiver is placed at a distance of  $x_R$  and constant height  $z_R = 2$  m with the orientation  $\theta$  with respect to the wind direction (Fig. 1). The implemented wind speed profile follows the power-law profile as in Eq. (3) with the wind speed  $U_{ref} = 8m/s$  at the reference height  $z_{ref} = 80m$  and wind shear exponents  $\alpha$ . The  $SPL_{ff}$  is

Table 1. Test cases done with  $x_R=500\text{m}$ , TDR  $\varepsilon=0.0115\text{m}^2/\text{s}^3$ , Ground parameter for Grass-summer:  $\sigma=354\text{kNs}/\text{m}^4$  and  $e=0.0157\text{m}$ , Grass-winter:  $\sigma=631\text{kNs}/\text{m}^4$  and  $e=0.006\text{m}$ .

Cases	$\theta(\text{deg})$	Ground	Wind shear exponent $\alpha$
A	80	Free field	-
B	180	Free field	-
C	80	Grass-summer	0.5
D	180	Grass-summer	0.2
E	180	Grass-winter	0.3

computed for the TEN and TIN between the frequencies between 100 Hz and 6000 Hz. For the propagation model, the influence of the scattering due to the turbulence  $\Delta L_{scat}$  and the atmospheric absorption  $\alpha_{abs}R$  are calculated for the same frequencies and all the segments at each height. The  $\Delta L_{PE}$  is calculated from 100 Hz until 2300 Hz using  $N_{hs}=7$  heights which are equally distributed between 35m to 125m as per the moving monopole model. The average value of  $\Delta L_{PE}$  of the 3<sup>rd</sup> octave frequency band at 2000 Hz is taken as the value of  $\Delta L_{PE}$  for the frequencies between 2300 Hz and 6000 Hz. We synthesize the signals of the wind turbine noise at the sampling frequency of  $f_s=44.1\text{kHz}$  between the frequencies  $f_{min}=100\text{ Hz}$  and  $f_{max}=6000\text{ Hz}$  for the few test cases which are described below. More signals are provided here: [\[link\]](#). In the signals provided, 0 dBFS corresponds to 0.1Pa. The spectrograms of the test cases are shown in Fig. 2 to 4. For a quantitative comparison of the different test cases, the time averaged SPL is plotted in Fig. 5a. The maximum computed difference in the amplitude that is observed by the receiver during the rotation of the wind turbine blades for each frequency is seen in Fig. 5b as the amplitude modulation (AM).

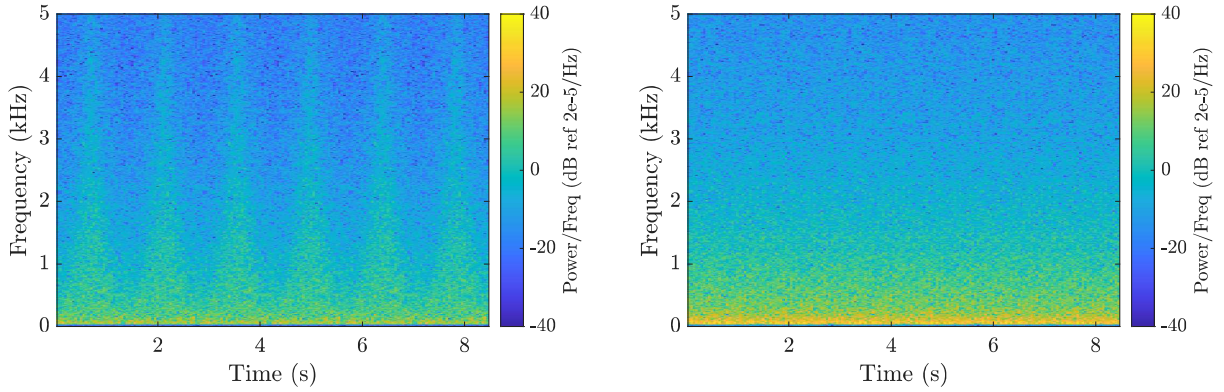


Figure 2. Spectrogram for cases A (left) and B (right)

From comparing the cases A, B with C, D and E it can be seen that the effect of the propagation is significant in the spectra generated as well as the AM (Fig.5). From case A and C that effect of the ground can be seen in the interference dips caused by the direct and ground reflected wave while the AM is the same for most frequencies but different for others. In the downwind condition as seen in cases B and D the interference dip is also seen but the AM is significantly different. This is because the wind turbine blades rotating in the inhomogeneous atmosphere experiences different amounts of propagation effects in the term  $\Delta L - \alpha_{abs}R$  at different heights. The effect of the type of ground and the wind shear exponent is seen in the cases D and E where the SPL is not very different as compared to the computed AM. For all the cases that include the propagation effects (C, D and E), it is seen that the generated AM is not the same for all frequencies.

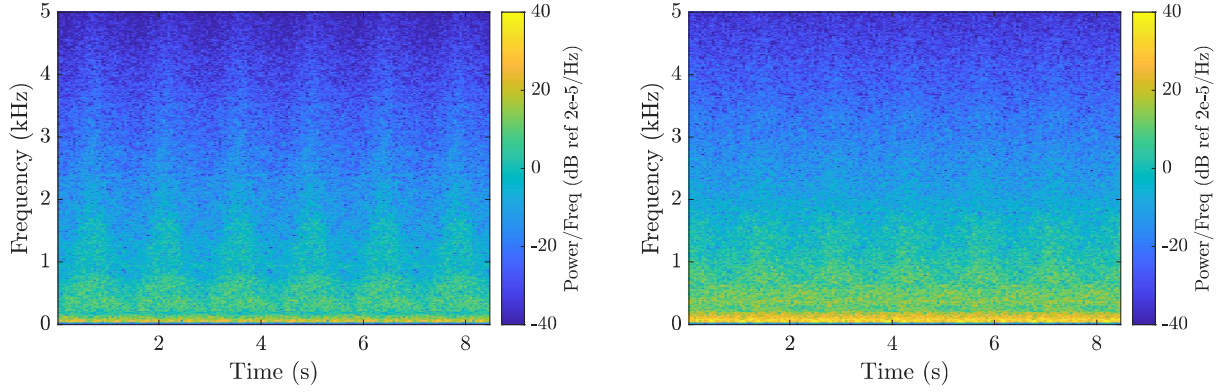


Figure 3. Spectrogram for cases C (left) and D (right)

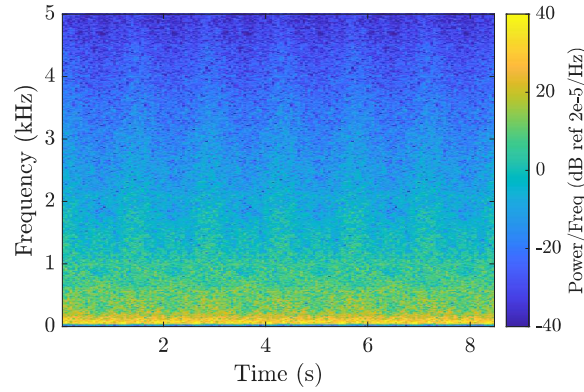


Figure 4. Spectrogram for case E

## 4 CONCLUSIONS

We present a physics-based synthesis model of wind turbine noise in a moving medium with ground effect and turbulence. The source model is based on Amiet's theory for the TEN and TIN. The propagation model uses the wide angle parabolic equation in a moving medium to consider the refraction due to the wind speed profile and ground reflection off the semi-porous ground. The effect of scattering due to turbulence is accounted for by using the Harmonoise model based on the Kolmogorov spectrum. The synthesis method of Mascarenhas *et al.* [13] is used to obtain time signals of the wind turbine noise under the specific desired conditions.

From the test cases it can be seen that the effect of the propagation significantly changes the response observed in free-field. The model is able to capture the effect of the wind profile on the propagated sound as well as the ground effect with realistic ground impedance parameters. The individual effects of the controllable parameters that contribute to the predicted sound can be studied further with the help of this model.

The effect of the scattering due to turbulence is mostly significant in the shadow zone of a particular point source. The computed result is a certain obtained level in the shadow zone depending on the amount of required turbulence. However, in the wind turbine noise model as an extended source, the effect of scattering of the sound in the shadow zone is not the same for all the heights and is thus the overall effect is not very significant. The turbulence effect on the phase and amplitude fluctuation may be important components which add realism to the signal which are yet to be added to complete the model. This physics-based synthesis model is relatively adaptive to the requirements of the study. This makes it an useful tool for further studies that can avail of this model. One such application is that use of this model for psychoacoustic analysis of the contribution

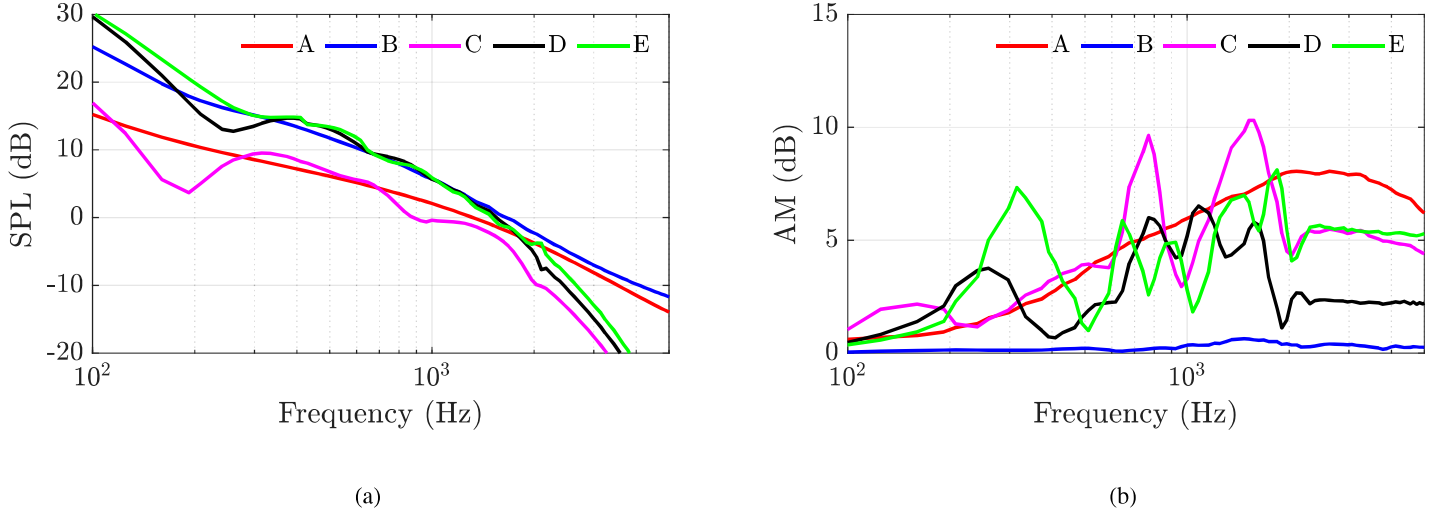


Figure 5. (a) Time-averaged SPL and (b) AM of the test cases that are given in Table.1

of individual components of the model on the impact of wind turbine noise. With this model we achieve a straightforward way to synthesize the noise observed from one wind turbine. We can proceed in this same course to synthesize an entire wind farm with this tool and thus study the noise on wind farm in the design phase itself .

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