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Sound propagation from a wind turbine in a hilly environment

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Sound propagation in the atmospheric boundary layer can be strongly affected by vertical gradients in the wind speed and air temperature, and by atmospheric turbulence. In addition, undulating terrain will either partly shield or focus sound waves, highly impacting sound exposure levels. These aspects become especially important in case of wind turbines present on a ridge, such placement often being efficient to harvest wind energy due to the wind speeding up. In this study, sound propagating from a wind turbine, positioned at a ridge, towards receivers along a valley, is numerically simulated with the Parabolic Equation (PE) method. A combination of an analytical starting field and the conformal mapping method shows to be a useful and numerically efficient approach, overcoming some issues as identified and discussed in this work. Example calculations show the importance of the valley ground impedance for wind turbine noise exposure.

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1. INTRODUCTION

Sound propagation in the atmospheric boundary layer can be strongly affected by vertical gradients in the wind speed and air temperature, and by atmospheric turbulence[1,2]. In addition, undulating terrain will either partly shield or focus sound waves, highly impacting sound exposure levels. These aspects become especially important in case of wind turbines present on a ridge, where wind energy harvesting can often be efficient due to wind speeding up.

There is only scant research regarding wind turbine noise propagation in such environments. In this work, the use of the Green's Function Parabolic Equation method (GFPE)[3] is explored to study sound propagation from a ridge wind turbine across an adjacent valley.

GFPE allows including refraction using the effective sound speed approach for rather arbitrary wind speed and temperature profiles, which can also be range-dependent. Ground impedance jumps along the propagation path can be easily modelled. Turbulent scattering can be approached by imposing small fluctuations on the sound speed profiles. In addition, GFPE is a computationally efficient technique, allowing to step in forward direction at multiples of the wavelength. In this way, the distances of interest with respect to wind turbine noise exposure and related annoyance, let's say 1 km, could be reached.

2. INCLUDING UNDULATING TERRAIN IN PE

Various approaches for introducing undulating terrain exist like the general terrain PE (GTPE)[4], the rotated reference frame approach[5,6,7], a stair-step terrain approach using Kirchoff's method[8], and the conformal mapping method[9,10].

The GTPE can be seen as a generalization of the Crank-Nicholson PE (CNPE) method. This method is applicable to arbitrary terrain profiles and uses terrain-following coordinates. However, analysis showed that the local slope angles should not exceed roughly 30 degrees[1]. In addition, CNPE is much less efficient than the GFPE as stepping in the propagation direction needs sub-wavelength discretisation.

The rotated reference frame approach is applicable to the GFPE. The curved ground is treated as a succession of flat zones with different slope angles. The sound field in each domain starts from an array of pressure values, orthogonal to the local slope, as calculated from the previous domain. A number of reduced propagation steps are thus needed near the interface to accurately construct the next domain's starting field, which can strongly increase computing times. Sudden slope changes along the propagation path are difficult to handle.

The stairstep approach might be attractive due to its simplicity. The terrain profile is reduced to a succession of (best-fitting steps), that will be considered as small vertical barriers. The part of the sound field that is covered by such a step is then set to zero. This method further needs a vertical coordinate shift to continue propagation from the top of the next stair. In this way, and when allowing variable step widths, there is great flexibility in approaching a terrain profile. However, only reflection on horizontal surfaces is modelled. This means, e.g., that waves reflected obliquely in the propagation direction cannot interfere further on along the propagation path. Only part of the acoustic energy will be sent in that direction due to diffraction at step corners.

In this study, the conformal mapping (CM) method will be used, which is a computationally highly efficient approach to account for undulating terrain. The CM method is based on the theoretically perfect analogy between a circularly curved ground surface with radius Rc and a refracting atmosphere with the following exponential sound speed profile c:

$$c = c_0 e^{\frac{z}{R_c}} \tag{1}$$

with R_c>0 for concave ground and R_c<0 for convex ground, z the height above the ground and c_0 the reference sound speed.

The shielding caused by convex terrain can thus be approached by sound propagating in an upwardly refracting atmosphere, while concave terrain is simulated by a downwardly refracting atmosphere. A change in sound speed profile comes at almost no additional computational cost in the PE model. Note that such artificially refracting atmospheres due to ground curvature are typically much stronger than those observed due to (real) wind flows in the atmospheric boundary layer. The latter, however, can be superimposed on the artificial profile by ground curving, and allows accounting for both terrain undulation and atmospheric refraction.

The main limitation here is the need for simplification to circularly curved terrain segments. Care is needed to account for the coordinate transform between the real (curved ground) system and the artificially refractive flat PE domain.

3. HYBRID MODEL

In this work, there is a specific interest in a ridge wind turbine emitting sound across the adjacent valley. A direct application of the conformal mapping approach would imply the source being positioned radial to the curved ground, which is not realistic.

The geometry of interest is therefore idealized to sound propagation over a small convex circular segment, representing the ridge, followed by sound propagation over part of a large concave cylinder, representing the valley (see Fig. 1).

3.1. Analytical starting field

A fundamental approximation when deriving the Parabolic Equation method is that sound propagation is only accurately described in a relative small cone, horizontally centred around the source. In the current context, neglecting this fact would artificially put a major part of the valley in an acoustic shadow zone, leading to inaccurate results.

To overcome this issue, the analytical solution for sound diffraction by an impedance cylinder[11] is used to produce the starting field orthogonal to the local slope (along the radius) of the valley part.

As shown in Fig. 1, sound propagation over exactly one quarter of the cylinder representing the ridge part is considered to facilitate the coupling to the valley part. This avoids complicated interpolation at the interface with the valley section.

3.2. Conformal mapping GFPE

The GFPE method is not only able to commence from a point source starting function as is common practice[1], but from any vertical array of pressures that can be accurately calculated at sub-wavelength spacing. One possibility is to use another numerical technique (see e.g. Ref. 12), or as is done here, an analytical solution. As a result, the current approach does not suffer from angle limitations in the source region, or from the fact that receivers are positioned at large heights relative to the ground radius, potentially causing problems with the conformal mapping approach[1]. Note that the starting function should be defined on a vertical grid with a (logarithmically) decreasing spacing towards higher positions. This is necessary to account for the conformal mapping coordinate transform from the curved surface to a grid with a uniform vertical spacing in an (artificially) refracting environment[1,4].

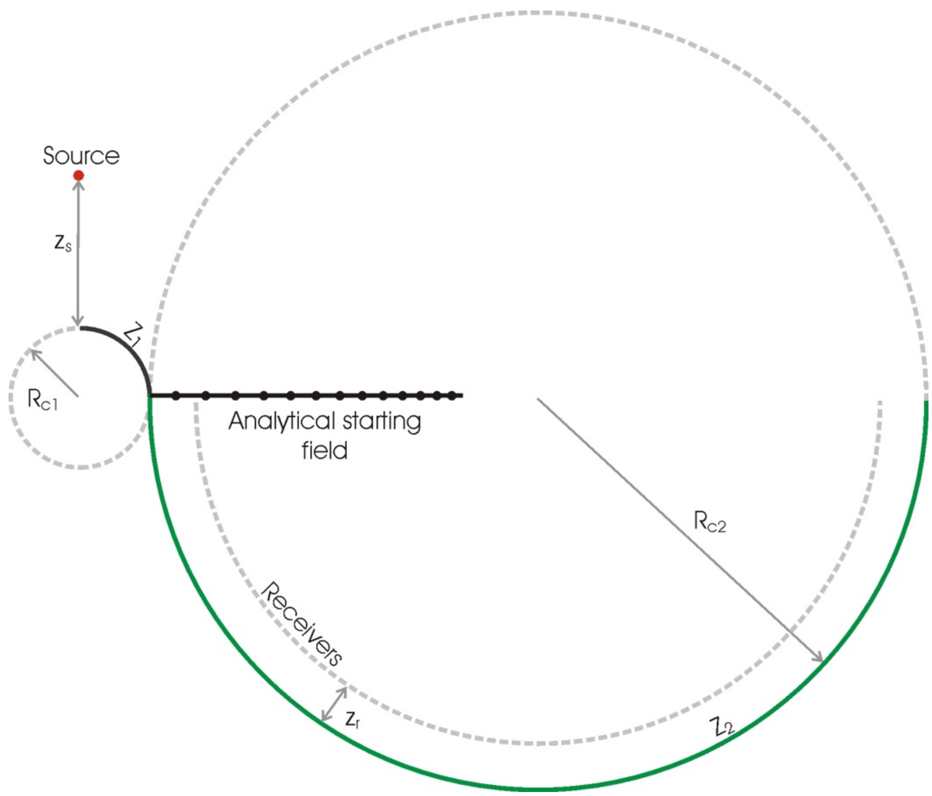

Figure 1. Geometry of the hybrid model for simulating sound propagation from an elevated sound source, positioned at a ridge (radius R_{c1}, source height z_s), towards a valley (radius R_{c2}, receiver heights z_r). Z_1 and Z_2 are the ground impedances of the ridge and valley part, respectively.

4. EXAMPLE CALCULATIONS

As an example, sound propagating from a point source (concentrating all the wind turbine's emitted acoustic energy at hub height) at a height of z_s=75 m on top of the ridge is considered. The ridge is rigid and has a radius R_{c1}=10 m. The valley has a radius R_{c2} of 500 m, being either rigid or grass-covered (using the common Delany and Bazley impedance model, with a flow resistivity of 200 kPa s/m^2). In Fig. 2, the sound pressure level distribution across the valley is depicted, at a fixed receiver height z_r=4 m (above the local ground). In both ground type scenarios, significant shielding is observed at the source side of the valley.

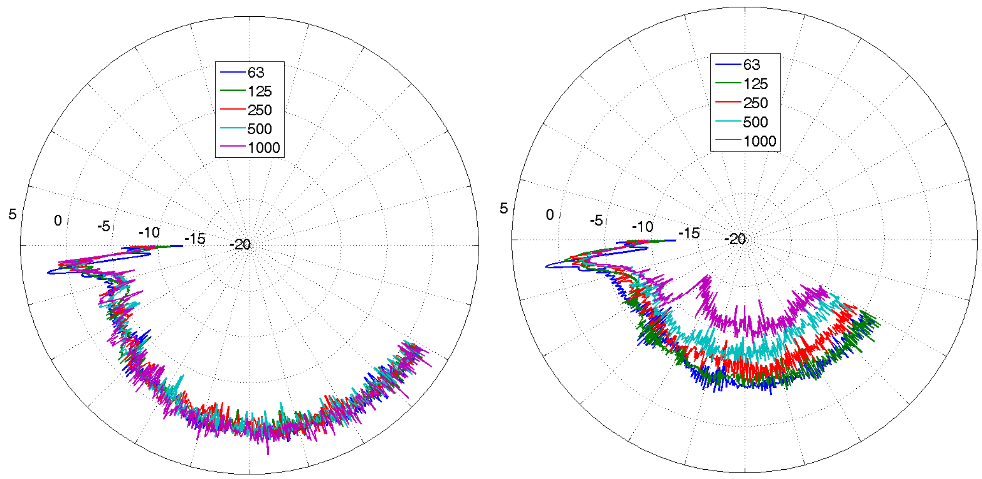

Figure 2. Predicted sound pressure levels (relative to free-field sound propagation) across the valley, in case of rigid ground (left) and a grass-covered valley (right). Octave bands with centre frequencies ranging from 63 Hz - 1 kHz were considered.

However, strong differences are predicted further along the valley. Starting from about the centre of the valley, near free-field sound propagation is predicted at all octave bands for the rigid ground, while there is a much stronger reduction for the grass-covered valley, for which effects become more pronounced with increasing sound frequencies.

Note that in the current simulations, in a first approach, a logarithmical wind speed profile (neutral atmosphere) is assumed that follows the valley terrain, using an aerodynamic roughness length of 0.05 m and a friction velocity of 0.4 m/s. Turbulence is neglected. Flow fields, however, will be strongly influenced by the terrain undulations and by the presence of the wind turbine.

5. CONCLUSIONS

Simulations with the proposed method show a pronounced asymmetry in exposure across the valley, with significant lower levels at its source side (relative to free-field sound propagation). At the far side of the valley, near free-field sound propagation is predicted in case of rigid ground. The valley's ground type has a strong effect on the wind turbine noise exposure. The proposed method could help in optimal placement of wind turbines at ridges when the adjacent valley is inhabited.

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