NUMERICAL MODELLING OF NOISE PROPAGATION IN THE ATMOSPHERIC ENVIRONMENT AND APPLICATION TO WIND ENERGY INSTALLATIONS

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ABSTRACT
The modelling of noise propagation in the atmosphere using a combination of two well-known methodologies is examined. The developed numerical model uses a normal modes methodology for the low frequency part and a ray theory methodology for the high frequency part. The capabilities and shortcomings of the model are discussed and indicative results are presented. The perspective is the application of this model to the propagation of the noise emitted from wind turbines or parks.

1 INTRODUCTION
Noise has become lately a significant restriction for wind energy applications. Isolated sites are difficult to find anymore so sites near populated regions come into play. This means that problems with public acceptance will be most probable. In this perspective it is necessary for the developers of wind parks to be in a position to correctly predict and control noise. To this end three major steps must be taken:

- Reliable estimation of the intensity of noise sources.
- Modelling of noise propagation and prediction at different ranges.
- Necessary modifications of the wind park design for reduction of noise levels.

All steps are included as research tasks of the JOULE-III project entitled "Investigation of Noise Emissions from Wind Parks and their Impact to the Design of Parks". The first step has been concluded giving a complete model for noise calculations from wind parks. Validation results are included in [1]. The present paper reports specifically on the progress made regarding noise propagation within this project.

Propagation of noise emitted from wind parks can be considered as a wave propagation problem in an inhomogeneous medium which can be treated under quite general assumptions within the framework of linear acoustics. In order to solve the acoustic equation a variety of methods have been developed and widely used in underwater acoustics [2,3]. After some necessary modifications they can also be applied to propagation problems in atmospheric environment.

In particular, to exploit these models for wind energy applications, the following features must be included: (a) the spatial variability of the mean velocity field, (b) the stratification of the atmosphere, (c) the terrain orography and (d) the ground acoustic characteristics.

A method of this kind has been recently set up at NTUA. It consists of an axi-symmetric model which takes into account the vertical profile of the mean wind velocity, the range dependence of the medium characteristics and the terrain effects through velocity variations and ground geometry.

In the sequel the model is described and results indicating the importance of the aforementioned parameters to noise propagation are presented.

2 METHODOLOGY
The problem of wave propagation is usually decomposed into two parts: the "low" frequency part which is treated by solving directly the acoustic equation, and the "high" frequency part which is usually treated by a ray tracing approach.

Two different codes representing the two different methodologies are used. The first is KRAKEN [4]; it applies the methodology of normal modes [2,3] which is able to give an exact representation of the acoustic field in a wide range of frequencies. The second is AERAS [5]; it applies the very popular methodology of ray theory [2,3], the accuracy of which increases with frequency.

The KRAKEN model takes into account the stratification of the air, the attenuation of the noise in the air and the ground, the terrain geometry and the range dependence of the wind velocity profile. In the case of downstream propagation, the equivalent sound is obtained from the summation of the sound speed plus the wind velocity which varies with height.

The height of the computational domain is divided into a number of equidistant intervals so that the modes are adequately sampled. Usually 10 points per wavelength are sufficient. This means that the computational time increases with frequency. That is the reason why ray theory models are preferred for high frequencies.

KRAKEN has the capability of using free, rigid and homogenous half-space options for boundary conditions. In the case of the atmosphere the under-ground layer is modelled as an acoustic half-space with the characteristics of the specific acoustic material. The upper-air layer is modelled as a finite acoustic medium with constant characteristics up to a certain height. Above that height it is considered as vacuum.

The AERAS model takes into account the terrain geometry and the range dependence of the acoustic parameters. The ground effect is introduced through the reflection coefficient. The stratification of the atmosphere is not taken into account. The top boundary is considered absorptive.
**Fig 1:** Normal modes, Frequency=11Hz, Receiver height=1m

**Fig 2:** Frequency=180Hz, Receiver height=15m

**Fig 3:** Ray diagram, Frequency=240Hz

**Fig 4:** Normal modes, Receiver height=1m

**Fig 5:** Ray theory, Receiver height=15m

**Fig 6:** Normal modes, Frequency=40Hz
3 RESULTS

Both methods give as output the acoustic pressure field in the form of the transmission loss. The transmission loss is defined as (see [2]):

\[ TL(r,z) = -20 \log \left( \frac{p(r,z)}{p_{0}(r=1)} \right) p_{0} = \frac{\epsilon^{\mu r}}{4\pi r} \]

where \( r \) is the range, \( z \) is the height, \( p_{0} \) is the pressure for the source in free space and \( p(r,z) \) is the pressure at point \( (r,z) \).

3.1 A simple test case

The problem of propagation of noise emitted from a point sound source over flat terrain is the first case examined. This case is also described in [6] where some measurements are taken from. The source is assumed to be a monopole located at 40m in height. The wind velocity profile follows a logarithmic law and the sound speed is considered constant and equal to 343m/s.

The purpose of this test consists in the initial estimation of the attenuation of noise as the distance from the source increases and the determination of the validity range of ray theory.

In Fig1 the predictions of the normal mode code are compared with the measurements reported in [6]. The frequency is equal to 11 Hz and the receiver height is equal to 0.5m. On account of the fact that the intensity of the source is unknown in the case of the experiment, the TL curve is shifted in order to make the comparison possible. A good agreement is observed between predictions and measurements.

In Fig2 the TL curves produced by the KRAKEN and AERAS codes are compared for frequency equal to 180 Hz. It is concluded that for frequencies higher than 150Hz the ray theory predictions are satisfactory far from the source. The receiver height is equal to 15m.

In Fig3 the ray diagram is presented when the frequency is equal to 240 Hz. It is clear in this figure the formation of a surface sound channel, where a part of the total acoustic energy is trapped.

3.2 The Carland Cross topography

The noise measurements at Carland Cross [7], which is a fairly smooth terrain, are used in order to evaluate the computational tool. The point source is a loudspeaker mounted at 29m above ground, whereas the receivers are eight microphones equally spaced within a distance of 350m, mounted at 1.2m above ground. In the case under consideration the wind velocity is perpendicular to the direction of propagation, so it does not affect the predictions significantly.

The measured noise includes also the background noise. In order to compare the predictions of the propagation model with the measurements the background noise level BL is added to the predicted noise level PL according to:

\[ TPL = 10 \log_{10} \left( 10^{\frac{PL}{10}} - 10^{\frac{BL}{10}} \right) \]

where TPL is the total noise level.

In the following tables the predictions of the propagation model are compared with the available measurements and the predictions of the IEA model (Noise levels are in dB).

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<tr>
<th>Table 1: Distance from the Tower Base: 50m</th>
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<td>Frequency</td>
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<td>PL (IEA)</td>
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<td>PL (Modes)</td>
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<td>TPL (Modes)</td>
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<th>Table 2: Distance from the Tower Base: 200m</th>
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<tr>
<td>Frequency</td>
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<td>PL (IEA)</td>
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<td>PL (Modes)</td>
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<td>TPL (Modes)</td>
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<tr>
<td>Frequency</td>
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In the above tables ML stands for the measured noise level. The agreement between the predictions and the measurements is satisfactory. The differences with the simple IEA model which assumes hemispherical propagation are in some cases significant, although the ranges where the experiments refer to are relatively near the source.

3.3 Investigation of various parameters

The simple test case was then used in order to investigate the effect of various parameters on the noise propagation.

a Frequency: In Fig4, the incoherent transmission loss TL (see [3]) is plotted versus range for various frequencies from 10 Hz up to 360 Hz when the normal modes code is used. The receiver height is taken equal to 1m. It is observed that the transmission loss increases with frequency. The same trend is observed when the ray theory code is used (Fig5). The receiver height is equal to 15m.

b Receiver height: In Fig6 the vertical variation of the transmission loss is shown for various ranges on the flat terrain. There is a region for the receiver in the vicinity of the source where the loss is significantly smaller even for the range of 900m.

c Terrain effects: The complexity of the terrain is one of the
factors that affects noise propagation significantly. A complex terrain not only places obstacles to the propagation but also changes the wind velocity profile which subsequently changes the sound speed. In Fig 7,8 the contour plots of the transmission loss are presented for the same case with and without a simple obstacle (two-dimensional hill). It is clear that the presence of the hill causes a decrease in the noise level near the ground. In Fig 9 the corresponding ray diagram is presented indicating a shadow zone behind the hill. The ray theory model cannot predict the noise level in this region. This is an inherent restriction of the ray theory.

4 DISCUSSION

A numerical model for the propagation of noise in the atmosphere has been described and evaluated. The effect of various parameters on the predictions was also examined. The model is based on the combination of two well known methodologies, the normal modes (low frequencies) and the ray theory (high frequencies). The normal modes model gives satisfactory predictions at the heights of interest (about 1m) as shown from the comparison with the existing measurements. The ray theory model is a fast tool useful for high frequencies and has the advantage of visualizing results in a comprehensive and descriptive way (ray diagrams). However, it presents two inherent restrictions: The first concerns the vertical discretization which does not allow predictions close to the ground and the second concerns the source opening angle which confines the energy within a cone. Work in the near future will focus on these two points. The propagation model in its final form along with the existing models [1] will complete the numerical tool for the prediction and propagation of noise emitted from a wind park.

5. ACKNOWLEDGEMENTS

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6. REFERENCES