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Acoustic effects of a tree simulated by a FDTD model

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Summary
Trees and forests as a natural noise barrier would be an eco-friendly solution for noise reduction, as they have additional positive effect for air quality too. To quantify the sound attenuation by trees, the simulation of sound propagation in and around forest areas requires a detailed understanding of the acoustic properties of single trees. Therefore the acoustic effects of different trees are investigated by means of a three-dimensional finite difference time domain (FDTD) sound propagation model within a frequency range from 50 to 1500 Hz. The choice of the model type instantaneously enables the consideration of multiple reflection and diffraction. The influence of trunk size, branch density and the shape of the tree on backscattering and transmission is studied. The spatial resolution in this case is 5 cm. The acoustic properties of real and idealized trees are compared and presented to attain a classification for the typical tree parameters. As earlier studies have shown the main effect results from the diameter of the trunk. Another important parameter is the density of branches within a volume. This is described by the partial volume and the partial cross section. The long-term objective of this study is to gain a new parameterization for a realistic implementation of canopy in sound propagation models.

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1. Introduction

Single trees, rows of trees or forests have an influence on sound propagation through reflection and scattering of sound wave by trunks, branches and twigs. Many studies have been made to quantify the influence of forests [1],[2],[3]. These include theoretical considerations (e.g. scattering by cylinders) [4], measurements and model simulations. With the FDTD model it is possible to resolve the tree trunk and major branches in three dimensions. The model is capable of simulating reflection as well as scattering of sound waves. The main questions to be answered are: Have different shapes an influence on the sound field? How the different parameters of trees do influence the sound field? Does the size of obstacles influence the spectrum of sound? Is it possible to simplify the model setup in a way that not all details of the trees are necessary?

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2. Method

The influence of single trees and other objects on the sound field around is examined by providing first a simulation for the free undisturbed field without any obstacles, then repeating this simulation with trees or some idealized obstacles in the center of the model domain. The observed effects of the porous objects are mainly backward reflection and scattering as well as forward transmission. Losses of energy due to upward scattering and ground absorption are neglected. To systematically rate the influence of trees on the sound field three steps of simplification are applied: (1) six types of natural (real) trees (the voxel data are obtained from laser scanning [5]), (2) six types of idealized trees with a known number of twigs and diameters and (3) six types of random patch field consisting of blocks of different size and density. Geometrical spreading, refraction, diffraction as well as reflection and scattering of sound waves can be described in high detail by solving the linearized Euler equations with a FDTD model developed by Heimann and Blumrich [6].

The particle velocity vector $\mathbf{U}''$ and the sound pressure p'' are predicted according to equation (1).

$$\frac{\partial \mathbf{U}''}{\partial t} = -\frac{1}{\rho_{met}} \nabla p''$$
$$\frac{\partial p''}{\partial t} = -\kappa\, p_{met} \nabla \cdot \mathbf{U}'' \qquad (1)$$

where $\mathbf{U} = \overline{\mathbf{U}} + \mathbf{U}' + \mathbf{U}''$ and $p = \overline{p} + p' + p''$ is composed of a mean wind speed vector $\overline{\mathbf{U}}$ and the mean air pressure $\overline{p}$, the turbulent deviations from these means $\mathbf{U}'$ and p' and the acoustical deviations $\mathbf{U}''$ and p''. ρ_{met} denotes the air density and $\kappa = c_p/c_v$. To investigate the influence of the trees, a 30 m long, 8 m wide and 24 m high model domain with a numerical resolution of 0.05 m was defined. A 16 m high obstacle (tree or patch field) with a diameter of 8 m was placed in the centre of the domain. As an example Figure 2 presents the birch in the center of the model domain. On the boundaries the projection of the tree is indicated in red colors. Two arrays of virtual receivers were placed 3 m in front and 3 m behind the obstacle. At these arrays the backscattered sound and the forward transmitted sound are registered. Cyclic boundary conditions in lateral y-directions are employed to realize an infinitely long row of trees as shown in Figure 1.

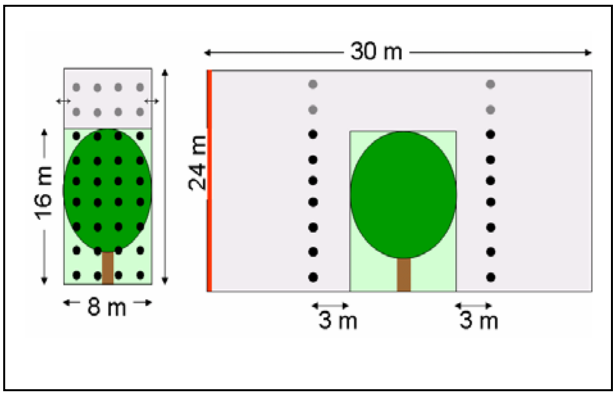

Figure 1. Scheme of the arrangement of the virtual microphones in the model domain around the tree or the central placed obstacle.

In the model simulations a plane sound pressure pulse, oriented parallel to the y-z-plane, which propagates in horizontal x-direction and penetrates the tree. Figure 3 provides a snapshot of the vertical cross section of the sound pressure field perpendicular to the row of trees after the pulse has passed the row. While the pulse front itself is hardly distorted, irregular patters around the tree indicate that sound is scattered and reflected in all directions.

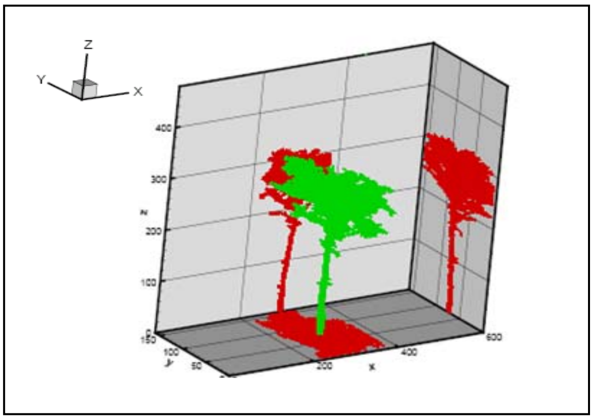

Figure 2: The birch (green) in the model domain with its shadowing (red) on the boundaries.

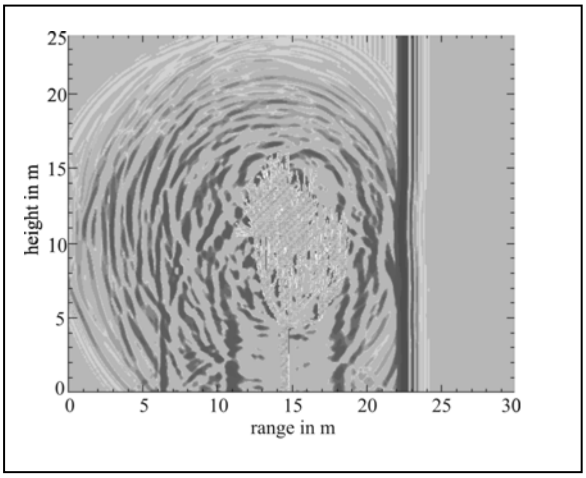

Figure 3: Snapshot of simulated sound pressure (vertical y-z cross-section through the centre of the domain) after the wave front has passed a row of idealized trees (type 1) from left to right

3. Properties of trees

The geometry of the trees is characterized by the “partial volume” and the “partial cross section”. The partial volume specifies the portion of filled grid cells to all grid cells in the enveloping volume (light green color in Figure 1). The partial cross section describes the area portion of the projection of the tree on the y-z-plane. It cloud be called also the shadow relief or the silhouette of the tree. The relation between these parameters is given in Figure 4.

In case of trees, the relation between partial cross section and partial volume is nearly log/linear. For other objects the relation depends on the distribution of the filled grid cells within the volume or the relation of the side area to the total volume. In Figure 4 one can recognize that the oak, the plane and the three spruces have a high partial tree volume as well as a high partial cross section. From the artificial trees only tree type 6 exceeds this.

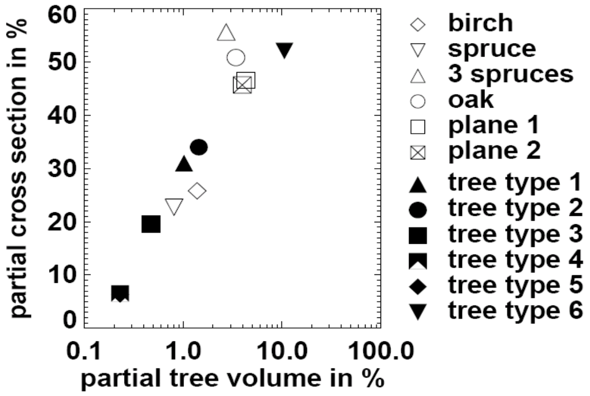

Figure 4: The relation between the partial tree volume and the partial cross section of various trees.

4. Results

The results of the simulations are analyzed under four aspects. First, the sound pressure level (SPL) in front of and behind a tree is recorded. Considering the reflected and transmitted sound in comparison to the undisturbed case, we obtain a relative SPL on the front section and on the back section as shown in Figure 5.

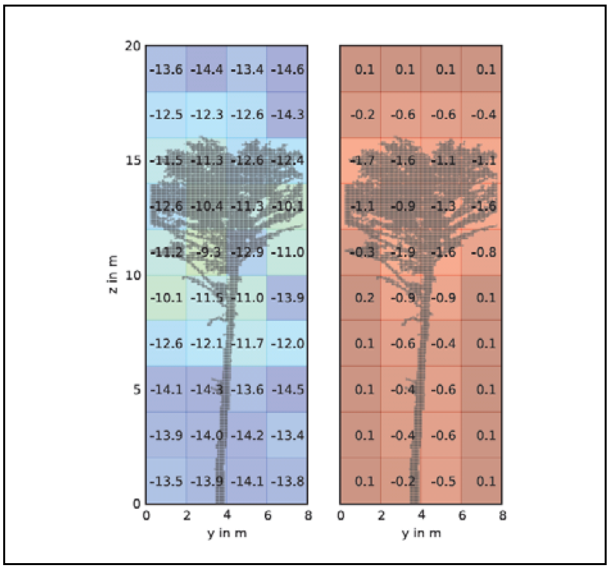

Figure 5: The sound field as recorded by the virtual microphones in front of (left hand side) and behind (right hand side) the birch relativ to the undisturbed case.

There is evidence about the influence of the shape of the tree or better about the distribution of the twigs of the tree on the sound field. In front of the tree the reflected sound energy is by 9 to 14 dB less than the incoming sound energy. The reflected sound energy is higher in regions where the twigs are denser. Behind the tree the attenuation ranges from +0.2 dB to -0.7 dB. The positive values appear where scattering leads to an amplification of sound behind the tree, while negative values correspond to the shadowing, especially near the trunk.

Second, performing a Fast Fourier Transformation on the registered sound pressure on the front section one can study the spectral effect of the tree objects on the sound propagation.

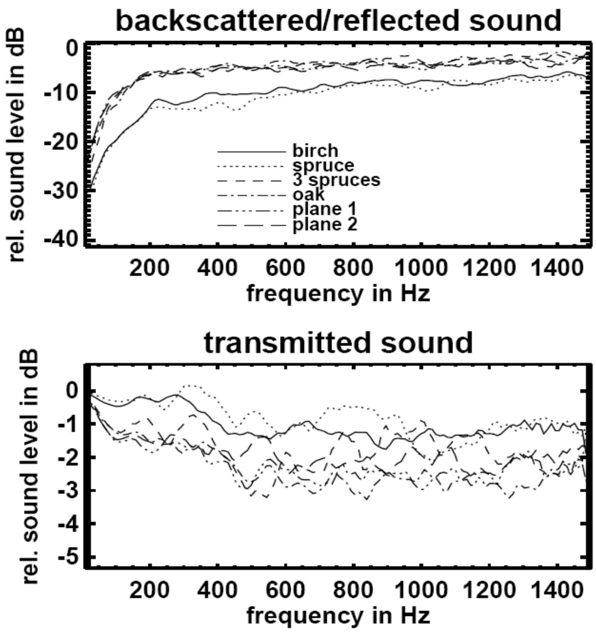

Figure 6. The averaged spectrum of all microphones in front of and behind the laser scanned trees. The backscattered (upper part) and the transmitted (below) sound is shown with sound levels relative to the undisturbed case.

In Figure 6 one can observe that sound waves of frequencies above 200 Hz are reflected much better than of lower frequencies. One can conclude that the sparse trees like birch and spruce (with a partial volume below 5% and a partial cross section less than 30%) reflect much less sound energy than the dense trees like the plane or the oak. Regarding the transmission one can conclude also that the effect of the sparse trees is smaller.

Third, the total effect of backscattering and transmission is plotted relative to the undisturbed sound field as a function of the partial tree volume and the partial cross section, as shown in Figure 7.

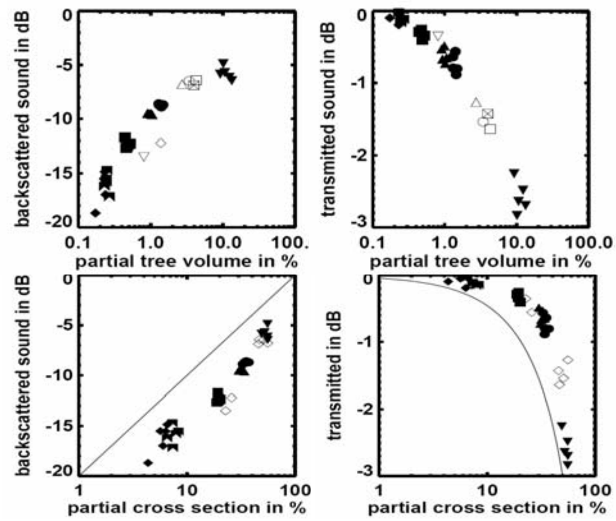

Figure 7: Backscattered sound (left side upper and lower panel) and transmitted sound (right side upper and lower panel) relative to the undisturbed sound as a function of the partial tree volume and the partial cross section. The symbols correspond to the trees shown in figure 3.

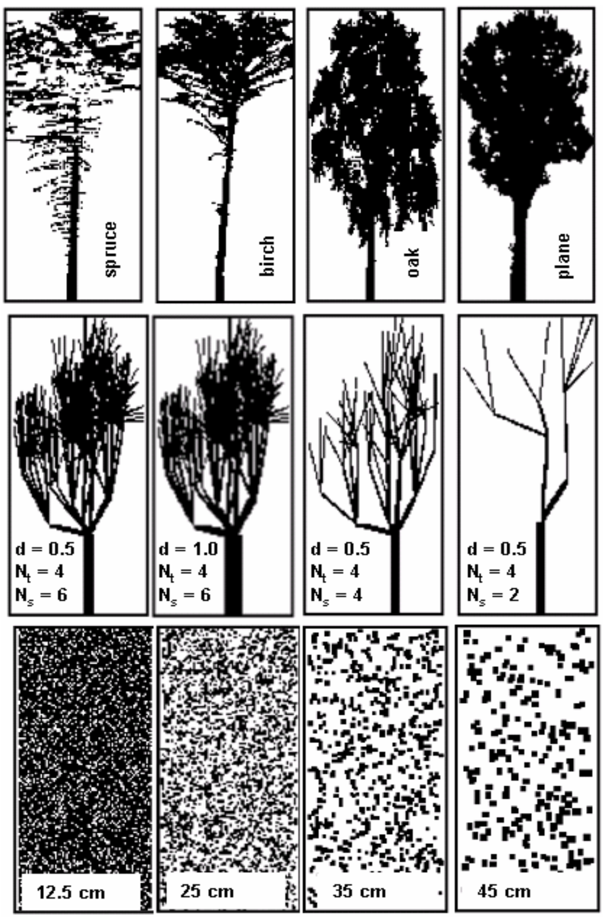

Figure 8. Silhouettes of laser scanned trees (upper row), idealized trees (middle row) with different parameter settings (d: diameter of trunk, Nt: number of branching orders, Ns: number of branches per branching order) and patches (lower row) with side length of 12.5 cm up to 45 cm. All objects are 16 m high with a (crown) diameter of 8 m.

From this analysis follows a regularity that suggests some functional relationship. In Figure 7 the theoretical function is plotted as thin lines. Every halving the partial cross section results in a 3 dB weaker backscattering signal. For transmission this 3 dB reduction can be observed also on halving the partial cross section from 100 to 50 %.

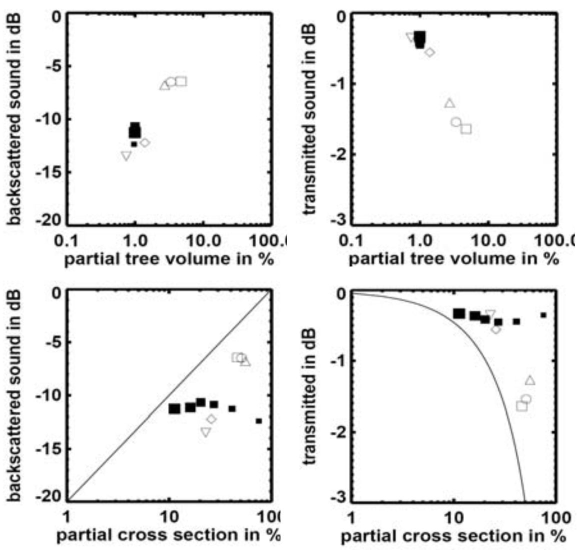

Figure 9: Comparison of backscattered sound (left side upper and lower panel) and transmitted sound (right side upper and lower panel) relative to the undisturbed sound between trees and patches as a function of the partial tree volume and the partial cross section. According to their extent the filled square symbols represent the patches.

The fourth step is the comparison of the simulation results for the laser scanned trees to the patches of different densities presented in Figure 8 together with most of the other trees used in the simulation. The patch field was generated keeping the partial volume constant (1.0 %) for all patch sizes. On varying the extension of the patch blocks the number of the blocks was reduced. The result is a variation in the partial cross section in the range from 70 % for the small blocks with a side length of 12.5 cm down to 10% for the big blocks with a side length of 65 cm. Their effect on the sound field is shown in Figure 9. The cross section of the patches cover a wider range than those of the trees, but their effect on the sound field is for all patch variations nearly the same (the backscattered sound reach from -11 dB to – 15 dB). The magnitude of backscattered and transmitted sound corresponds to the result of the trees with similar parameters.

5. Conclusions

The presented simulations show a clear interrelation between the shadowing effect of trees on the sound field and the characteristics of the trees. This could be checked more profound on applying artificial trees and objects of adjustable parameters like the patches into the model domain and comparing their influence on the sound field with the real trees. The effects of the artificial trees fit very well to the sound field of the real trees. Including a patch field into the model domain the explicit dependency between the partial cross section, the partial volume and the effect on the sound field could be studied systematically. The development of a simplified formula according to these findings seems to be possible.

Acknowledgements

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